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Titanium Minerals Availability—Market Economy Countries

A Minerals Availability Appraisal

By R. J. Fantel, D. A. Buckingham, and D. E. Sullivan

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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PREFACE

The Bureau of Mines Minerals Availability Program is assessing the worldwide availability of nonfuel minerals. The Bureau collects, compiles, and evaluates information on active and developing mines, explored deposits, and mineral processing plants worldwide. The program's objectives are to classify domestic and foreign resources, to identify by cost evaluation resources that are reserves, and to prepare analyses of mineral availabilities.

This report is part of a continuing series of reports analyzing the availability of minerals from domestic and foreign sources and those factors affecting availability. Analyses of other minerals are in progress. Questions about the Minerals Availability Program should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E Street, NW., Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	mt/h	metric ton per hour
d/yr	day per year	mt/yr	metric ton per year
g/mt	gram per metric ton	pct	percent
ha	hectare	US¢/kW•h	U.S. cent per kilowatt hour
h/yr	hour per year	US¢/L	U.S. cent per liter
kg/m³	kilogram per cubic meter	US¢/mt	U.S. cent per metric ton
km	kilometer	US$/1b	U.S. dollar per pound
km²	square kilometer	US$/mt	U.S. dollar per metric ton
m	meter	US$/yr	U.S. dollar per year
min	minute	wt pct	weight percent
mm	millimeter	yr	year
mt	metric ton		

TITANIUM MINERALS AVAILABILITY—MARKET ECONOMY COUNTRIES

A Minerals Availability Appraisal

By R. J. Fantel,[1] D. A. Buckingham,[2] and D. E. Sullivan[3]

ABSTRACT

The Bureau of Mines investigated the resource availability of titanium minerals from 63 mines and deposits in 12 market economy countries. These mines and deposits contain, at the demonstrated resource level, an estimated 438 million metric tons (mt) of titanium dioxide (TiO_2) in the minerals rutile, ilmenite, leucoxene, and anatase. An additional 314 million mt of TiO_2 is available from inferred resources.

If all titanium minerals and other recovered heavy minerals are sold at total costs at least equal to the January 1984 market prices, approximately 200 million mt of contained TiO_2 could be recovered in total. In terms of mineral concentrates, this equals approximately 11 million mt of rutile concentrate, 187 million mt of ilmenite concentrate, 3 million mt of leucoxene concentrate, 13 million mt of synthetic rutile concentrate (in addition to the ilmenite), and 89 million mt of titanium slag.

The study indicates that world resources of low-cost rutile are declining. In order to maintain future supply for high-grade titanium resources, alternate sources will need to be developed, which may include higher cost rutile mines, Brazilian anatase deposits, increased production from slag operations, or more synthetic rutile capacity from ilmenite resources, which are abundant.

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INTRODUCTION

For many years titanium, in the form of titanium dioxide (TiO_2), has primarily been used as a source for pigments. Its whiteness, high refractive index, and light-scattering ability make it an excellent whitening agent for paints, paper, rubber, plastics, and other miscellaneous items. More recently, though, titanium metal has become important in the defense and aerospace industries owing to its high strength-to-weight ratio and its resistance to corrosion. Small quantities of TiO_2, in the form of rutile, are also used for welding rod coating. Ceramic capacitors for electronics use small quantities of titanium.

Titanium is the ninth most abundant element in the Earth's crust and occurs in many mineral species. Only a few of these minerals contain enough titanium to be of commercial importance. They are ilmenite ($FeTiO_3$), rutile (TiO_2), and leucoxene (an upgraded alteration product of ilmenite). Ilmenite, theoretically 53 pct TiO_2 and 47 pct FeO, can be found in numerous mineral occurrences. Its titanium content may often be greater than the theoretical amount, owing to oxidation, which removes iron and calcium and frequently occurs in sand deposits, producing titanium contents of as much as 65 to 70 pct TiO_2. This form is known as altered ilmenite (or leucoxene, arizonite, or pseudoritite). Rutile is also found in numerous mineral occurrences; it is theroretically 100 pct TiO_2, although it seldom contains more than 95 pct. Other titanium minerals occasionally found in economic concentrations are brookite, perovskite, anatase, and sphene.

The purpose of this study is to evaluate the worldwide resources of titanium minerals and to assess the related costs of production to recover these minerals. This study is of strategic importance to the United States, which, although one of the largest producers of TiO_2 pigments as well as titanium metal, imports significant quantities of the raw materials for their manufacture. The study presents separate analyses of key producing countries of titanium minerals and discusses the potential substitution of other titanium minerals for rutile in the production of high-grade TiO_2. An analysis of the availability of byproduct zircon resources also is presented.

Data for foreign mines and deposits in the evaluation were provided by Kaiser Engineers, Inc., under contract J0215037. Data for domestic mines and deposits were developed for this study by personnel of the Bureau's Field Operations Centers in Pittsburgh, PA, Denver, CO, and Spokane, WA.

ACKNOWLEDGMENTS

The authors wish to thank Langtry E. Lynd, titanium commodity specialist, Bureau of Mines, Division of Nonferrous Metals, and Eric R. Force, resource specialist, U.S. Geological Survey, for their assistance in preparing this report.

EVALUATION METHODOLOGY

DATA ANALYSIS

The data collected for this report are stored, retrieved, and analyzed in a computerized component of the Bureau's Minerals Availability Program (MAP). The flow of the Minerals Availability evaluation process from deposit identification to analysis of availability information is illustrated in figure 1.

The analysis methodology is as follows:

1. The quantity and grade of titanium resources were evaluated in relation to physical and technological conditions that affect production from each deposit as of the study date, January 1984.

2. Appropriate mining and processing methods were described for producing operations and proposed for nonproducing deposits. Related capital and operating costs were estimated, including a transportation cost to deliver the titanium concentrate to a pigment plant or the marketplace. For purposes of consistency, it was assumed that all titanium concentrates were transported to a local port or marketplace for export unless they were being used for internal domestic consumption. If they were to be internally consumed, the concentrates were considered to be transported to nearby pigment plants. For certain potential byproduct sources of ilmenite, the concentrate was assumed to be stockpiled rather than sold.

3. An economic analysis of each operation determined the average total production cost over its entire producing life, including a predetermined discounted-cash-flow rate of return (DCFROR) on invested capital, and the associated total demonstrated tonnage of titanium concentrates that could potentially be recovered. A 15-pct DCFROR was used for this study.

4. Upon completion of the individual property analyses, all properties included in the study were simultaneously analyzed, and the data were aggregated and transferred onto titanium availability curves. Separate curves were generated for each titanium mineral (i.e., rutile and ilmenite) unless too few deposits prohibited a curve. If a deposit produced more than one titanium mineral, it was included on more than one curve. These curves are aggregations of total potential titanium concentrates that could be produced over the life of each operation, ordered from the lowest total cost deposits to the highest. The curves illustrate the comparative costs associated with any given level of potential total output and provide an estimate of what the average long-run titanium concentrate price (in January 1984 dollars) would have to be in order for a given tonnage to be potentially available. The long-run price, which each operation would require to cover its average total cost of titanium concentrate production, would provide revenues sufficient to cover the average total cost of

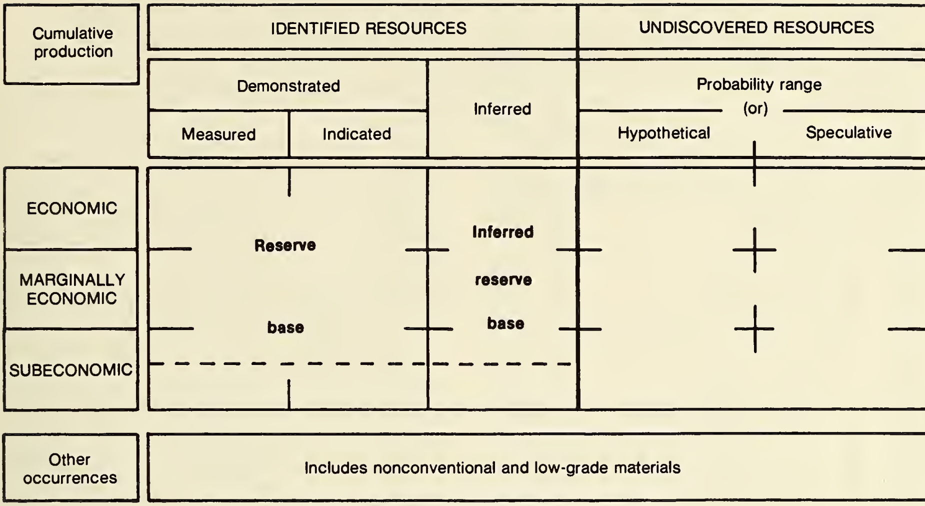

Figure 1.—Flowchart of MAP evaluation procedure.

production, including a return on investment high enough to attract new capital.

DEPOSIT SELECTION CRITERIA

Selection of deposits was limited to known deposits that have significant demonstrated reserves or resources. As related to this study, reserves are (titanium) mineralizations that can be mined, processed, and marketed at a profit under prevailing economic and technologic conditions. Resources are (titanium) concentrations in such form and amount that economic extraction is currently or potentially feasible but not proven (*1*).[4]

For the deposits analyzed, tonnage estimates were made at the demonstrated resource level, based on the mineral resource-reserve classification system (fig. 2) developed jointly by the Bureau and the U.S. Geological Survey (*1*). The demonstrated resource category includes measured plus indicated tonnages. Generally, reserve and resource tonnage and grade calculations were computed from specific measurements, samples, or production data, and from estimations made on geologic evidence.

Resources analyzed had to be recoverable using current mining and milling technology. In addition, the U.S. deposits had to conform to certain basic guidelines that have been established by Bureau and Geological Survey titanium commodity specialists in a recently published report (*2*). In general, the guidelines are as follows:

1. Titanium minerals must be coarser grained than 0.02 mm, since finer grains cannot presently be separated.
2. If a deposit contains ilmenite-magnetite intergrown grains, the grains must be separable unless they contain 25 pct or more TiO_2, in which case, they can be smelted into high-TiO_2 slag.
3. Unconsolidated deposits must contain at least 1.0 pct ilmenite (approximately 0.5 pct TiO_2) or 0.1 pct rutile (approximately 0.09 pct TiO_2) or combinations of the two. Hard-rock deposits have to have at least 10 pct ilmenite or perovskite (5.3 pct TiO_2), or 1.0 pct rutile (0.95 pct TiO_2). When titanium can be produced as a byproduct from other minerals for which the economics are demonstrated, the above cutoffs can be disregarded.
4. Deposits must contain more than 100,000 mt of contained TiO_2.

These criteria are minimal ones used to admit a deposit to the resource class. Requirements in the present report are more stringent, and thus many deposits listed in reference *2* are omitted here.

Foreign deposits included in the analysis had to meet one of the following criteria:

1. Producing properties accounting for at least 85 pct of the titanium production from each country that has in recent years produced significant quantities of titanium concentrates.
2. Developing and explored deposits where the demonstrated titanium reserve-resource quantity was at least 150,000 mt of contained TiO_2.
3. Past-producing deposits where the remaining demonstrated titanium reserve-resource quantity was at least 150,000 mt of contained TiO_2.

For this study, a total of 63 mines and deposits were evaluated (17 domestic and 46 foreign), which meet at least the lower limits of the selection requirements set forth above. All deposits evaluated are from market economy countries. Additional resources either from centrally planned economy countries or at the inferred or hypothetical resource levels are discussed in the text but are not included in the economic evaluations.

[4]Italicized numbers in parentheses refer to items in the list of references preceding the appendixes at the end of this report.

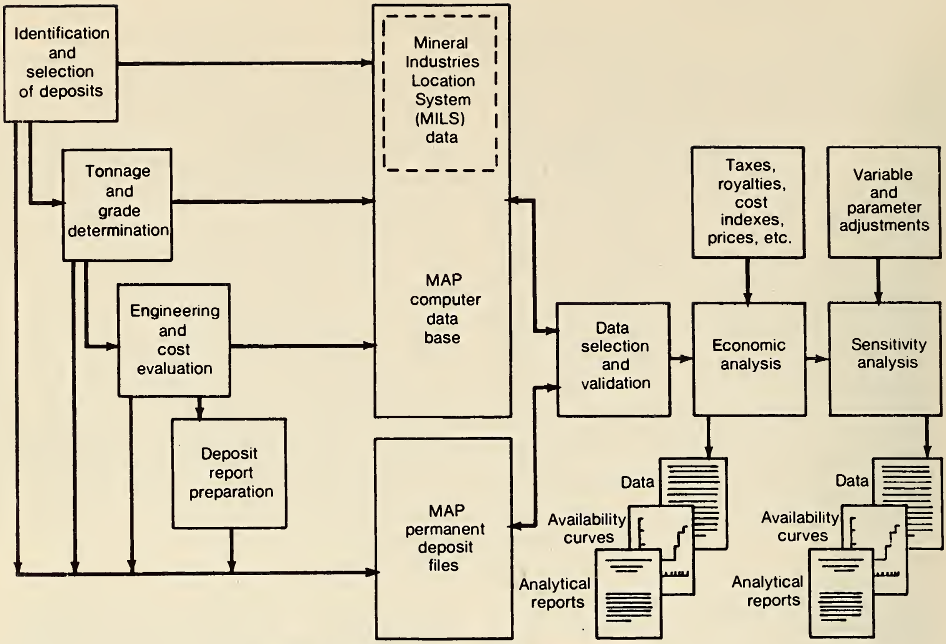

Figure 2.—Mineral resource classification categories (*1*).

THE WORLD TITANIUM INDUSTRY

Titanium metal is a strategic and critical metal. TiO_2 pigment is the predominant white pigment used in paints, paper, plastics, rubber, etc. Titanium metal is widely used in high-performance aircraft and other applications where corrosion resistance is necessary. Only about 5 pct of titanium minerals is used to make titanium metal, and nearly all of the remainder is used in pigment (*3*). Figure 3 shows the flow of titanium minerals to the pigment plant and metal stage.

The majority of the world's rutile, typically 91 to 95 pct TiO_2, is produced in Australia, Sierra Leone, and the Republic of South Africa. It can be used in titanium metal plants, directly to coat welding rods, or in chloride process pigment plants.

Ilmenite and leucoxene are much more abundant than rutile. Ilmenite may contain as much as 50 to 70 pct TiO_2, and leucoxene as much as 87 pct TiO_2 (and even 91 pct from some Australian operations). They are generally used in sulfate process pigment plants although when upgraded to synthetic rutile they can be used in the chloride plants. The chloride plants can accept high-iron feeds (such as ilmenite), but since this method consumes chlorine, it is rarely practiced.

Ilmenite is also used to produce a titanium slag, which is a higher grade titanium concentrate. The slag from Sorel,

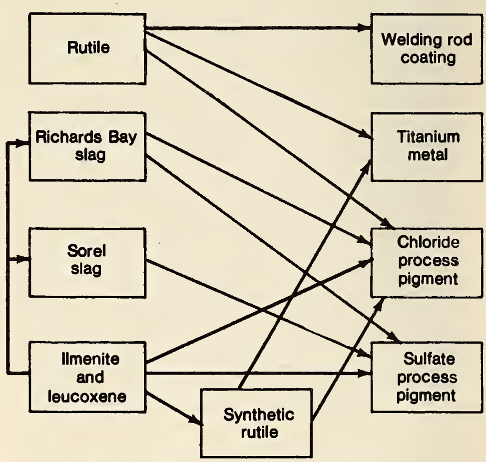

Figure 3.—Flow of titanium mineral products.

Quebec, Canada, has in the past graded approximately 70 pct TiO_2, although it is presently (as of 1984) 80 pct. The Sorel slag (as it is called in the industry) feeds sulfate pigment plants. Richards Bay slag (Republic of South Africa) grades 85 to 87 pct TiO_2 and feeds both sulfate and chloride pigment plants (*3*, p. 11).

PRODUCTION

Table 1 lists, by country, the production of titanium concentrates for the years 1961, 1971, 1981, and 1983 (estimated). The table shows that for all the titanium concentrates an increase has occurred in production over the past two decades. The values for 1983 are listed to illustrate that in recent years, owing to world economic conditions, production of titanium concentrates has declined slightly in most countries.

Australia is the largest producer of ilmenite and leucoxene. As shown on the table and in figure 4, Australia produced 37 pct of the ilmenite and leucoxene mined during 1981. Norway produced over 18 pct, and the United States and the U.S.S.R. produced almost 14 and 12 pct, respectively. During the 20-yr period shown in table 1, when world production of ilmenite doubled, production from Australia increased eightfold.

Australia accounted for approximately 64 pct of the 1981 world production of rutile. Sierra Leone and the Republic of South Africa each produced about 14 pct.

Titaniferous slag was produced primarily in two countries during 1981; Canada produced just over two-thirds and the Republic of South Africa produced the remainder. In the Sichuan Province of China, very small amounts of slag are also produced (on the order of 1,000 mt/yr).

Seven major companies and the State of Western Australia mined and produced titanium mineral concentrates from 10 mines in Australia during 1981. The companies are Associated Minerals Consolidated Ltd., Rutile & Zircon Mines (Newcastle) Ltd. (RZ Mines), Mineral Deposits Ltd., Cable Sands Pty. Ltd. (owned by Kathleen Investments), Allied Eneabba Pty Ltd. [59 pct owned by E.I. du Pont de Nemours & Co., Inc. (Du Pont)], Westralian Sands Ltd., and Consolidated Rutile Ltd. In addition, four mines in Australia were being developed by three companies, Mineral Deposits Ltd., Murphyores Holding Ltd., and Associated Minerals Consolidated Ltd.

Four mines produced titanium mineral concentrates in the United States during 1981. They were owned by three companies—Associated Minerals (USA) Ltd. Inc., Du Pont, and NL Industries, Inc. Companies that have produced titanium concentrates in the recent past include ASARCO Incorporated[5] and American Cyanamid Co.

[5]The Asarco operation closed in 1981. This analysis considers the mine to be shut down; substantial redevelopment would be required for the mine to again produce.

Table 1.—World production of titanium concentrates (*4-6*)

(Thousand metric tons)

Concentrate type and country	1961	1971	1981	1983[e]
Ilmenite and leucoxene:				
Australia:				
Ilmenite	169	829	1,321	875
Leucoxene	0	0	19	18
Brazil	NA	10	15	15
China[e]	NA	NA	136	140
Finland	19	140	161	160
India	174	66	162	150
Japan	0	3	0	0
Madagascar	4	0	0	0
Malaysia[1]	109	156	172	190
Norway	311	641	658	544
Portugal	([2])	1	([2])	([2])
Senegal	17	0	0	0
South Africa, Republic of	90	0	0	0
Spain	30	.24	0	0
Sri Lanka (formerly Ceylon)	3	93	80	82
United Arab Republic	34	0	0	0
U.S.S.R[e]	NA	NA	426	435
United States[3]	709	620	492	W
Total	1,670	2,582	3,644	2,609
Rutile:				
Australia	103	367	230	172
Brazil	([2])	([2])	([2])	([2])
India	1	3	6	7
Senegal	([2])	0	0	0
Sierra Leone	0	12	51	72
South Africa, Republic of	3	0	50	56
Sri Lanka (formerly Ceylon)	0	3	14	8
United Arab Republic	[e]1	0	0	0
U.S.S.R.[e]	NA	NA	10	10
United States	8	0	W	W
Total	117	385	362	326
Titaniferous slag:				
Canada[4]	420	774	759	612
Japan[4]	2	5	0	0
South Africa, Republic of[5]	0	0	370	381
Total	422	779	1,129	993

[e]Estimated.
NA Not available.
W Withheld to avoid disclosing company proprietary data.
[1]Exports.
[2]Less than 500 mt.
[3]Includes a mixed product containing ilmenite, leucoxene, and rutile.
[4]Contains 70 to 74 pct TiO_2 (Sorel slag now 80 pct).
[5]Contains 85 to 87 pct TiO_2

NOTE:—Data may not add to totals shown because of independent rounding.

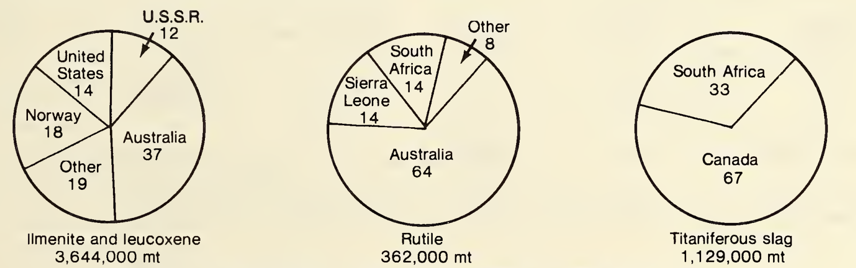

Figure 4.—Total production of titanium concentrates by mineral types, 1981.

Other countries with operations included in this study are—

Canada, one producer, QIT-Fer et Titane Inc. (QIT), which is owned by Standard Oil Co. of Ohio (SOHIO);

Brazil, one producer, owned by Titanio do Brasil (TIBRAS), as well as a developing deposit owned by Cia. Vale do Rio Doce (CVRD); both are governmentally owned companies;

Finland, one producer, Rautaruukki Oy, which is Government owned;

Norway, one producer, Titania A/S, owned by NL Industries;

India, three producers and one developing deposit, all owned by the Government of India;

Sri Lanka, one producer, which is Government owned;

Sierra Leone, one producer, owned by Sierra Rutile Ltd. (which is wholly owned by Nord Resources Corp. of Ohio);

Republic of South Africa, one producer, which is owned by a consortium with majority interest held by QIT of Montreal, Canada, and Union Corp. and Industrial Development Corp. (IDC), both of Johannesburg, Republic of South Africa.

Synthetic rutile was produced in Australia, India, Japan, the United States, and Taiwan. Each of these countries has at least one synthetic rutile plant, the largest being the Kerr-McGee Chemical Corp. plant in Mobile, AL. The mines and deposits in this analysis, including their ownership and status, are listed in table 2.

Table 2.—Ownership and status of titanium mines and deposits in market economy countries

	Status[1]	Deposit type[2]	Mining method	Milling method	Ownership	Products[3]
NORTH AMERICA						
United States:						
Arkansas: Magnet Cove	PP	HR	Open pit	Magnetic-electrostatic	Numerous private owners	R
California: Ione	([4])	P	Dredging	Magnetic	North American Refractories Co.	I, Z
Colorado: Powderhorn	EXP	HR	Open pit	Magnetic-electrostatic	Buttes Gas and Oil Co.	P, RE
Florida:						
Green Cove Springs	PRD	P	Dredging	..do	Associated Minerals (USA) Ltd. Inc.	R, I, L, Z, RE
Highland Operation	PRD	P	..do	..do	E.I. du Pont de Nemours & Co., Inc.	M, Z
Trail Ridge Operation	PRD	P	..do	..do	..do	M, Z
Georgia:						
Brunswick-Altamaha	EXP	P	..do	..do	Union Camp Corp., Jones family.	M, R, Z, RE
Cumberland Island	EXP	P	..do	..do	U.S. National Park Service	M, Z
New Jersey: Manchester	PP	P	..do	..do	ASARCO Incorporated	I
New York: MacIntyre Development.	PRD	HR	Open pit	Flotation	NL Industries, Inc.	I, Fe
North Carolina: NL Industries.	EXP	P	..do	Magnetic-electrostatic	..do	I
Oklahoma: Otter Creek Valley.	EXP	P	Placer mining	Magnetic	Numerous private owners	I
Tennessee:						
Silica Mine	([4])	P	Open pit	Magnetic-electrostatic	Tennessee Silica Sand Co.	I, R, L, Z, O, RE
Oak Grove	EXP	P	Dredging	..do	Ethyl Corp.	I, R, Z, RE
Virginia:						
B. F. Camden Anomaly	PP	HR	Open pit	..do	Private ownership	I
Piney River	EXP	HR	Open pit-sublevel caving.	Flotation	S. U. Wilkcens, Jr.	I
Wyoming: Iron Mountain	EXP	HR	Open pit	Gravity-magnetic[5]	Rocky Mountain Energy Co., The Anaconda Company.	S, Fe
Canada:						
Allard Lake	PRD	HR	..do	Magnetic-electrostatic[5]	QIT-Fer et Titane, Inc. (SOHIO).	S, Fe
Pin-Rouge Lake	EXP	HR	..do	..do	Laurentian Titanium Mines Ltd.	S, Fe
SOUTH AMERICA						
Brazil:						
Bananeira	EXP	HR	..do	Flotation	Mineracao Itaqui	A
Camaratuba	PRD	P	Strip level	Magnetic-electrostatic[5]	Titanio do Brasil	R, I, Z
Campo Alegre de Lourdes	EXP	HR	Open pit	..do[5]	Cia. Bahiana de Pesquisa Metais.	S, Fe
Catalao	EXP	HR	..do	Flotation	Metais de Goias S. A., Goias Fertilizantes S.A.	A
Tapira	DEV	HR	Strip level	..do	Cia. Vale do Rio Doce	A
EUROPE						
Finland: Otanmaki	PRD	HR	Sublevel stoping	..do	Rautaruukki Oy (Government)	I, Fe, O
Italy: Piampaludo	EXP	HR	Strip hillside	..do	Mineraria Italiana S.p.A. Milan.	R, I, G
Norway: Tellnes	PRD	HR	Open pit	Gravity flotation	NL Industries Inc.	I, Fe, O

See footnotes at end of table

Table 2.—Ownership and status of titanium mines and deposits in market economy countries—Continued

	Status[1]	Deposit type[2]	Mining method	Milling method	Ownership	Products[3]
ASIA						
India:						
Chavara (IREL)	PRD	P	Strip level	Magnetic-electrostatic	Indian Rare Earths, Ltd. (Government).	R, I, L, Z, RE
Chavara (KMML)	PRD	P	Dredging	..do	Kerala Minerals & Metals Ltd. (Government).	R, I, L, Z, RE
Manavalakurichi	PRD	P	Strip level	..do[6]	Indian Rare Earths, Ltd. (Government).	I, R, SR, Z, RE
Orissa-Chatrapur	DEV	P	Dredging	..do	..do	I, R, Z, RE, SR
Sri Lanka: Pulmoddai	PRD	P	..do	..do	Ceylon Mineral Sands Corp. (Government).	I, R, Z, RE
AFRICA						
Sierra Leone: Mogbwemo	PRD	P	..do	..do	Sierra Rutile Ltd.	R
South Africa, Republic of: Richards Bay.	PRD	P	..do	..do[5]	QIT, Union Corp., Industrial Development Corp.	S, R, Fe, Z
OCEANIA						
Australia:						
New South Wales:						
Bridge Hill Ridge	PRD	P	Dredging	Magnetic-electrostatic	Mineral Deposits Ltd.	R, I, Z
Evans Head	EXP	P	..do	..do	State of New South Wales	R, I, Z
Munmorah	PP	P	..do	..do	Associated Minerals Consolidated Ltd.	R, I, Z, RE
Stockton Bight	EXP	P	..do	..do	Mineral Deposits Ltd.	R, I, Z
Tomago Sand Pits	PRD	P	..do	..do	Rutile & Zircon Mines (Newcastle) Ltd.	R, I, Z
Yuraygir National Park	PP	P	..do	..do	State of New South Wales and Federal Government.	R, I, Z
Queensland:						
Agnes Waters	EXP	P	..do	..do	Mineral Deposits Ltd.	R, I, Z
Cooloola	PP	P	..do	..do	State of Queensland and Federal Government.	R, I, Z, RE
Curtis Island	EXP	P	..do	..do	Murphyores Holdings Ltd.	I, R, Fe, Z
Fraser Island	PP	P	..do	..do	Murphyores Holdings Ltd., Dillingham Minerals.	R, I, Z, RE
Gladstone Mainland	EXP	P	..do	..do	Murphyores Holdings Ltd.	I, R, Fe, Z
Moreton Island (MDL)	EXP	P	..do	..do	Mineral Deposits Ltd.	R, I, Z
Moreton Island (Murphyores)	EXP	P	..do	..do	Murphyores Holdings Ltd.	R, I, Z
North Stradbroke (AMC)	PRD	P	..do	..do	Associated Minerals Consolidated Ltd.	R, I, Z, RE
North Stradbroke (CRL)	PRD	P	..do	..do	Consolidated Rutile Ltd.	R, I, Z, RE
Western Australia:						
Allied Eneabba	PRD	P	Strip level	..do	Allied Eneabba Pty. Ltd.	R, I, L, Z, RE
Australind	EXP	P	Ground sluicing	..do	Associated Minerals Consolidated Ltd.	I, R, L, Z
Barrambie	EXP	HR	Open pit	Magnetic[5]	Ferrovanadium Corp. N.L.	S, Fe
Cable Sands	PRD	P	Dredging	Magnetic-electrostatic	Kathleen Investments	I, R, Z, RE
Capel	PRD	P	..do	..do[6]	Associated Minerals Consolidated Ltd.	I, R, L, SR, RE
Cataby	EXP	P	..do	..do	Metals Exploration Ltd., Alliance Minerals NL.	R, I, Z, RE
Cooljarloo	EXP	P	Strip level	..do	Western Mining Corp. Holdings Ltd.	R, I, L, Z, RE
Eneabba	PRD	P	..do	..do	Associated Minerals Consolidated Ltd.	SR, I, R, L, RE
Gingin	EXP	P	..do	..do	Westralian Sands Ltd., Lennard Oil NL.	R, I, L, Z
Jurien Bay	PP	P	..do	..do	Western Mining Corp. Holdings Ltd.	I, R, L, Z, RE
North Capel	PRD	P	..do	..do	State of Western Australia	I, R, L, Z, RE
Scott River	EXP	P	Dredging	..do	..do	I, R, L, Z
Yoganup Extended, Boyanup, Tutunup.	PRD	P	Open pit	..do	Westralian Sands Ltd.	I, R, L, Z, RE
New Zealand: Barrytown	EXP	P	Dredging	Magnetic-electrostatic[5].	Fletcher-Challenge Ltd.	I, R, SR, Z, RE

[1]DEV = developing deposit; EXP = explored prospect; PP = past producer; PRD = producer.
[2]HR = hard-rock deposit; P = placer (or sand) deposit.
[3]The first product listed was assumed to be the primary product for this study. A = anatase concentrate; Fe = iron, magnetite, or pig iron; G = garnet; I = ilmenite concentrate; L = leucoxene concentrate; M = mixed ilmenite-leucoxene concentrate; P = perovskite concentrate; R = rutile concentrate; RE = rare earth oxide concentrate (monazite); S = titanium slag; SR = synthetic rutile concentrate; Z = zircon concentrate; O = other miscellaneous (sulfides, precious metals, vanadium, pyrite, etc.).
[4]These deposits are producers of silica sand, but not heavy minerals. Assumed as EXP for this study.
[5]After beneficiation, the ilmenite concentrate is smelted in an electric furnace.
[6]After beneficiation, some or all of the ilmenite concentrate is further upgraded in a synthetic rutile plant.

EXPORTS, IMPORTS, AND CONSUMPTION

Exporters of titanium concentrates have been, in recent years, primarily Australia, Canada, India, Malaysia, Norway, Sierra Leone, and the Republic of South Africa. The exports discussed in the following paragraph represent world exports as they existed in the late 1970's and early 1980's.

More than 23 pct of Australian exports of ilmenite and leucoxene were shipped to the United States; about 18 pct went to the United Kingdom; almost 15 pct went to the U.S.S.R.; and almost 8 pct went to Japan. The remainder went to unknown destinations. Almost 47 pct of Australian exports of rutile were shipped to the United States, more than 15 pct to the United Kingdom, more than 10 pct to the Netherlands, and over 6 pct to Japan (fig. 5) (*7*). The remainder went to unknown destinations. Canada exported titanium slag to Belgium, England, France, Federal Republic of Germany, Holland, Italy, Japan, and the United States (*8*). Sierra Leone exported its rutile mainly to the United States, with some to Europe (*9*). Europe receives 59 pct of the Republic of South Africa's slag exports, North America receives 23 pct, and Japan receives 18 pct (*10*). Norway exported almost 45 pct of its ore and ilmenite concentrate to the Federal Republic of Germany, over 12 pct to the U.S.S.R., and almost 11 pct to Poland (fig. 6) (*11*). Malaysia exports nearly all of its ilmenite concentrate to Japan. India exports to Japan, the Federal Republic of Germany, and China.

The United States consumed 776,700 mt of ilmenite concentrate during 1981; 214,300 mt or over 27 pct of this was imported (table 3, fig. 7). Most of these imports, over 89 pct, came from Australia, and about 10 pct came from the Republic of South Africa (table 4).

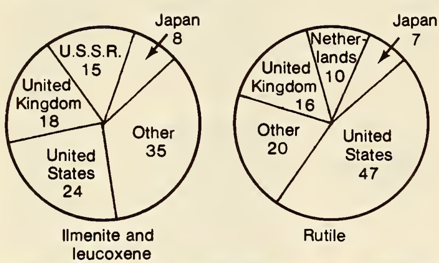

Figure 5.—Exports of titanium minerals from Australia in early 1980's. Numbers within pies refer to percent of total exports.

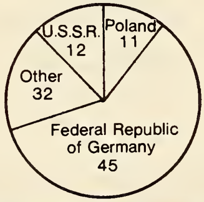

Figure 6.—Exports of ore and ilmenite concentrate from Norway in early 1980's. Numbers within pie refer to percent of total exports.

Table 3.—U.S. total consumption of titanium concentrates and related imports for consumption in 1981 (*6*)

Concentrate	Total consumption, 10^3 mt	Imports for consumption	
		10^3 mt	pct[1]
Ilmenite	776.7	214.3	27.6
Titanium slag	229.3	243.9	106.4
Rutile:			
Natural	258.9	146.1	70.9
Synthetic		37.5	

[1]Percentage of total consumption.

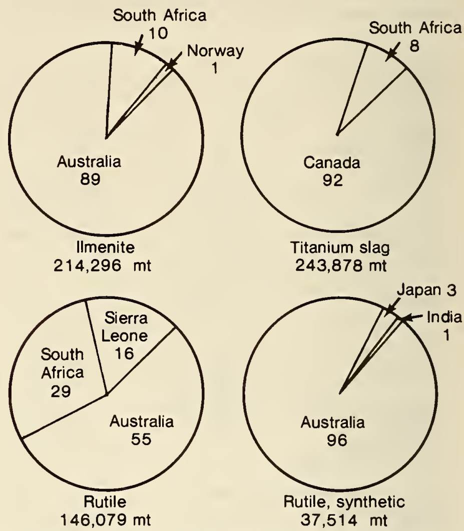

Figure 7.—U.S. imports of titanium concentrates, 1981. Numbers within pies refer to percent of total imports.

The United States consumed 229,300 mt of titanium slag during 1981, all of which was imported. During 1981, slag imports for consumption were more than 6 pct greater than consumption, indicating that some were stockpiled. The United States consumed 258,900 mt of rutile and synthetic rutile during 1981; about 71 pct of this was imported, 146,100 mt of rutile and 37,500 mt of synthetic rutile. About 55 pct of rutile imports were from Australia, over 29 pct from the Republic of South Africa, and 16 pct from Sierra Leone. Synthetic rutile imports were mostly from Australia, 96 pct, with about 3 pct from Japan and 1 pct from India and other.

PIGMENT PLANT PRODUCTION

Pigment manufacture utilized about 91 pct of 1981 U.S. consumption of titanium concentrates (*6*). Pigment is produced from ilmenite or slag in sulfate process plants and from rutile (both natural and synthetic), slag, and occasionally high-grade ilmenite and leucoxene in chloride process plants. The product from pigment production ranges from about 87 to 100 pct TiO_2. The decision as to which plant

Table 4.—U.S. imports for consumption of titanium concentrates, by country, 1981[1] (*6*)

Concentrate and country	Imports, mt
Ilmenite:	
Australia	191,256
Norway	1,502
South Africa, Republic of	21,538
Total	214,296
Titanium slag:	
Canada	223,295
South Africa, Republic of	20,580
Other	3
Total	243,878
Rutile, natural:	
Australia	80,147
Malaysia	10
Sierra Leone	22,894
South Africa, Republic of	43,007
Other	23
Total	146,079
Rutile, synthetic:	
Australia	36,023
India	399
Japan	1,089
Other	3
Total	37,514

[1]Adjusted by the Bureau of Mines.

NOTE:—Data may not add to totals shown because of independent rounding.

to build relates to the availability of either sulfuric acid or chlorine in addition to the availability of the raw material feed. If pollution is not a factor and sulfur is easily obtainable, the sulfate plant is often selected. Cost and availability of the titanium concentrate may also influence the plant process selection. Primarily because of environmental considerations (particularly sulfate emissions), no new sulfate plants have been built in the United States since the early 1970's; some plants have closed during this time.

Table 5 shows that as of the late 1970's[6] there were four sulfate process pigment plants in the United States with a combined capacity of 249,700 mt/yr. Since that time, the NL Industries plant, with a capacity of 100,000 mt/yr, has closed; also, there have been various expansions of capacities and changes in ownership for other plants (see table 5 footnotes). The table also shows that there were nine domestic chloride process plants producing TiO_2 pigment, with a combined capacity of 670,200 mt/yr. There were 39 sulfate and 7 chloride plants in foreign countries.

The United States had only 14 pct of the annual world capacity from sulfate pigment plants and 77 pct from chloride pigment plants.

The Federal Republic of Germany and Japan are also significant sulfate pigment producers, and the United Kingdom is one of the few countries outside the United States with significant chloride pigment production.

[6]The reports used to develop the table are dated 1981 for the U.S. plants and 1978 for the foreign plants.

Table 5.—Titanium pigment plant input source and type and output capacity (*6, 12*)

Company and location of plant	Raw material		Pigment capacity, mt/yr	
	Source	Type	Sulfate	Chloride
MARKET ECONOMY COUNTRIES				
NORTH AMERICA				
United States:				
American Cyanamid Co.:[1]				
Savannah, GA	Imported	Rutile	0	40,800
Do	..do	Slag, ilmenite	49,900	0
E. I. du Pont de Nemours & Co. Inc.:				
Antioch, CA	..do	Rutile	0	31,800
DeLisle, MI	..do	Mixture	0	136,100
Edge Moor, DE	Domestic	..do	0	100,500
New Johnsonville, TN	..do	..do	0	206,800
Gulf & Western Natural Resources Group Chemicals Div. (formerly New Jersey Zinc Co.):[2]				
Ashtabula, OH[2]	Imported	Rutile and synthetic rutile	0	27,200
Gloucester City, NJ[3]	..do	Slag	39,900	0
Kerr-McGee Chemical Corp.: Hamilton, MI[4]	Mixed	Synthetic rutile, rutile, and high-grade ilmenite	0	50,800
NL Industries, Inc.: Sayreville, NJ[5]	Domestic	Ilmenite	100,000	0
SCM Corp., Glidden Pigments Group, Chemical-Metallurgical:				
Ashtabula, OH	Imported	Rutile	0	38,100
Baltimore, MD	Mixed	Ilmenite, slag	59,900	0
Do	Imported	Rutile	0	38,100
Total, United States			249,700	670,200
Canada:				
Canadian Titanium Pigments, Ltd.: Varennes, Quebec.	Domestic	Slag	28,000	0
Tioxide of Canada Ltd.: Tracy, Quebec	..do	..do	30,000	0
Total, Canada			58,000	0
Mexico: Pigmentos y Productos Quimicos S.A.: Tampico.	Imported	Unknown	0	30,000
SOUTH AMERICA				
Brazil:				
Titanio do Brasil S.A.: Camacari.[6]	Domestic	Ilmenite	35,000	0

See footnotes at end of table.

Table 5.—Titanium pigment plant input source and type and output capacity (*6, 12*)—Continued

Company and location of plant	Raw material		Pigment capacity, mt/yr	
	Source	Type	Sulfate	Chloride
	MARKET ECONOMY COUNTRIES—Continued			
EUROPE				
Belgium:				
Bayer SA: Anvers	Imported	Slag	25,000	0
Kronos Titan (NL): Langerbrugge	..do	..do	40,000	0
Total, Belgium			65,000	0
Finland: Vourikemia Oy: Pori	Mixed	Ilmenite	80,000	0
France:				
Thann et Mulhouse:				
Le Havre	Imported	Ilmenite	80,000	0
Thann	..do	..do	20,000	0
Tioxide SA: Calais	..do	Slag	60,000	0
Total, France			160,000	0
Germany, Federal Republic of:				
Bayer SA:				
Uerdingen	..do	..do	70,000	0
Unknown[7]	Imported	Rutile	0	20,000
Kronos Titan:[8]				
Leverkusen	..do	Ilmenite, slag	70,000	0
Nordenham	..do	Ilmenite	66,000	0
Unknown	..do	Rutile	0	36,000
Pigment-Chemie GmbH: Homberg	..do	Slag	50,000	0
Total, Federal Republic of Germany			256,000	56,000
Italy: Montedison S.p.A.:				
Scarlino[9]	..do	Slag, ilmenite	54,000	0
Spinetta-Marengo[10]	..do	..do	43,000	0
Total, Italy			97,000	0
Netherlands: Tiofine: Rozenburg	Imported	Slag	35,000	0
Norway: Kronos Titan A/S: Fredrikstad	Domestic	Ilmenite	25,000	0
Spain:				
Dow Unquinesa, Axpe-Bilbao: Erandio	Mixed	..do	27,000	0
Titanio S.A.: Huelva	..do	..do	40,000	0
Total, Spain			67,000	0
United Kingdom:				
Laporte Titanium:[11]				
Stallingborough	Imported	Synthetic rutile and rutile	0	40,000
Lincs, Lincolnshire	..do	Slag, ilmenite	65,000	0
Tioxide:				
Billingham	..do	..do	27,000	0
Greatham	..do	Rutile	0	30,000
Grimsby	..do	Ilmenite	90,000	0
Total, United Kingdom			182,000	70,000
Yugoslavia:				
Cinkarna: Celje, Slovenia Republic	Unknown	Unknown	20,000	0
ASIA				
India: Travancore Titanium Products:				
Trivandrum	Domestic	Ilmenite	24,000	0
Kerala Minerals & Metals Ltd.	..do	Rutile and synthetic rutile	0	28,000
Japan:				
Fuji Titanium Industry Co., Ltd:				
Hiratsuka, Kanagawa Prefecture	Imported	..do	14,000	0
Kobe, Hyogo Prefecture	..do	..do	8,000	0
Furukawa Mining Co. Ltd.: Osaka	..do	..do	24,000	0
Ishihara Sangyo Kaisha, Ltd.:				
Yokkaichi, Mie Prefecture	..do	Ilmenite, slag	90,000	0
Unknown[12]	Domestic	Synthetic rutile	0	20,000
Sakai Chemical Industry Co. Ltd.: Onahama.	Imported	Ilmenite	30,000	0
Tiekoku Kako Co. Ltd.: Okayama	..do	..do	27,000	0
Titan Kogyo KK: Ube, Yamaguchi Prefecture.	..do	..do	13,000	0
Tohoku Chemical Co. Ltd.: Akita, Akita Prefecture.	..do	..do	12,000	0
Total, Japan			208,000	20,000

See footnotes at end of table.

Table 5.—Titanium pigment plant input source and type and output capacity (*6, 12*)—Continued

Company and location of plant	Raw material		Pigment capacity, mt/yr	
	Source	Type	Sulfate	Chloride
	MARKET ECONOMY COUNTRIES—Continued			
ASIA—Continued				
Korea, Republic of: Hankook Titanium Ind. Co. Ltd.: Seoul.	Imported	Unknown	4,000	0
Taiwan: China Metal Chemical: Taipei	..do	..do	6,000	0
AFRICA				
South Africa, Republic of: South African Titan Products: Umbogintwini.	..do	..do	30,000	0
OCEANIA				
Australia:				
Laporte Titanium:[8] Bunbury	Domestic	Ilmenite	30,000	0
Australian Titan Products: Burnie	..do	..do	27,000	0
Total, Australia			57,000	0
	CENTRALLY PLANNED ECONOMY COUNTRIES			
Czechoslovakia:				
Prerovske Chemicke Zadovy Prerov	Unknown	Unknown	30,000	0
Spotek: Ostrava	Imported	Ilmenite	12,000	0
Total, Czechoslovakia			42,000	0
Poland: Z.P.N.: Police	..do	..do	30,000	0
U.S.S.R.: State-owned	Unknown	Unknown	Unknown	Unknown
Grand total			1,730,700	874,200

[1]Recently added a combined 9,100-mt/yr capacity to its plants.
[2]Purchased by SCM Corp. in 1983. Chloride capacity now rated at nearly 32,000 mt/yr, with plans to expand to 38,000 mt/yr.
[3]Shut down in 1983.
[4]Plans are to expand the chloride plant capacity to 58,000 mt/yr in 1984, then to 65,000 mt/yr in 1986.
[5]As of the study date, January 1981, this was a producing operation. It has since shut down (in September 1982).
[6]As of study date, capacity reported to be 50,000 mt/yr.
[7]As of study date, reported to be shut down.
[8]Plans are to more than double the chloride plant capacity and reduce the sulfate plant capacity.
[9]As of study date, this plant was owned by Tioxide.
[10]This plant is presently closed.
[11]Laporte sold its TiO_2 interests to SCM Corp. in September 1984, and plans are to increase capacity to 105,000 mt/yr.
[12]Plans are to expand to 36,000 mt/yr.

STOCKPILES AND RECYCLING

Rutile is the only titanium mineral concentrate held in the National Defense Stockpile. As of January 1983, the quantity of rutile in the stockpile amounted to 35,000 mt, 37 pct of the stockpile goal established in 1980 (*3*). The sponge metal form of titanium is also stockpiled. The amount in the stockpile as of January 1983 was 29,000 mt, or only 17 pct of the stated goal. Although some limited recycling of titanium metal occurs, there is none at the concentrate or pigment stages.

BYPRODUCTS

Titanium deposits often contain other minerals, which may be recovered with the titanium and improve the economics of the operation. These minerals include zircon, monazite, garnet, sillimanite, and kyanite.

From an economic standpoint, zircon is typically the most important nontitanium byproduct. It is widely used in refractories, pigment glazes, foundry sand, and alloys. It is also used in explosives, lamp filaments, special magnets, and miscellaneous specialty items. The availability of zircon concentrates from the titanium mines and deposits in this study is discussed in a later section, "Availability of Byproduct Zircon."

The mineral monazite is recovered for its thorium and rare-earth content. Monazite is a cerium phosphate, but thorium is often substituted for cerium along with lanthanum and other rare earths. It is separated with the zircon in the beneficiation processes. Monazite is widely used as a source of color-producing elements on television tubes.

Garnet is sometimes recovered, depending on the market. It is used exclusively as an abrasive. The market for garnet is not widespread since it is cheaply available throughout the world.

Sillimanite and kyanite are aluminum silicates that are interchangeable for most uses. The predominant use is as a ceramic refractory ingredient. Because they are abundant and other minerals can be used in their place, in some operations they are rejected in tailings.

Pig iron is produced in titanium slag operations. It is an integral part of these operations and an important source of revenue. For this study, all operations that produced a titanium slag product also sold a pig iron byproduct.

Titanium minerals are themselves potential byproducts of porphyry copper operations, kyanite mines, massive sulfide ores, silica sand pits, some types of bauxites, and numerous other operations. Titanium minerals currently are produced as byproducts of placer tin mining in Southeast Asia.

MINING AND BENEFICIATION METHODS

MINING

Titanium ore can be mined by both surface and underground methods, although surface mining, principally for sand deposits, is most commonly used. Of the 63 deposits in this study, all but 2 used or were proposed to use 1 of 3 surface mining methods: dredging, strip level, or open pit.

Dredging is the typical surface mining method for placer beach sand deposits. This method is used for deposits in Australia (east coast), Sierra Leone, the Republic of South Africa, and the United States. Types of dredges most often used are cutterhead suction dredges and, in some cases, bucket-ladder dredges. Floating on water, dredges advance forward through the ore. If the dredged ore is soft and at depths of 20 m or less, the suction-cutter type is used. This dredge is often equipped with hydraulic jets to loosen and agitate the sand banks prior to drawing the ore toward the suction pipeline. The suction pipeline moves a slurry of sand, organic matter, and other waste to oversize screens and detrashing trommels. After organic matter and oversize (greater than 5 mm) and other waste is removed, the ore is deslimed if necessary, using hydrocyclones and/or hydrosizing. Preliminary concentration may take place on the dredge or on barges alongside, using gravity separation devices. A typical "wet mill" with gravity circuits may have gravity separation devices carrying out rougher, cleaner, and recleaner duties, with banks of spirals upgrading recleaner concentrate. High-grade deposit operations may employ scavenging gravity concentrators to recover more of the middlings. The tailings are stacked behind the dredge.

Factors such as ore body location (usually several kilometers inland), size and shape, and lithology, or lack of an adequate water supply may make the use of dredges for some placer deposits impractical. In those instances, other surface mining methods, including draglines and/or front-end loaders (FEL's) and trucks, are used. Ore is either stockpiled for blending or placed in a slurrying sump before going to rough concentration. These methods are typical of mines in Western Australia and Sri Lanka.

Open pit or underground methods are used on all hard-rock titanium deposits. Finland's Otanmaki Mine, using a sublevel stoping method, is the only underground mine producing titanium in this study. The Piney River, VA, deposit was proposed to combine an open pit using FEL's and trucks, and underground sublevel caving using load-haul-dump to recover the remaining ore tonnage. Open pit methods that require little or no blasting and use FEL's and trucks for ore and waste haulage are proposed for deposits in Brazil and the United States. Hard-rock deposits in Canada, Italy, Norway, and the United States will require extensive blasting. Diesel or electric shovels and trucks or FEL's and trucks are proposed for ore and waste haulage.

The only exception to the above mine descriptions are the Indian coastal beach sand deposits, where natural concentrate beach sand is skimmed by hand using shovels and buckets, baskets, or handcarts to transport the ore to stockpiles. The ore is then taken by conveyor, hand-pushed mine car, or canoe directly to a "dry mill."

BENEFICIATION

Titanium ores mined from placer beach sand deposits are processed through preliminary concentration in "wet mills," with final concentration taking place in "dry mills" (figs. 8-9). In wet mills, ore is separated, using wet-gravity methods, into a heavy-mineral fraction containing the titanium raw materials and a lighter mineral fraction (tails). Ore from a dredge or slurry sump is pumped at 25 to 30 pct

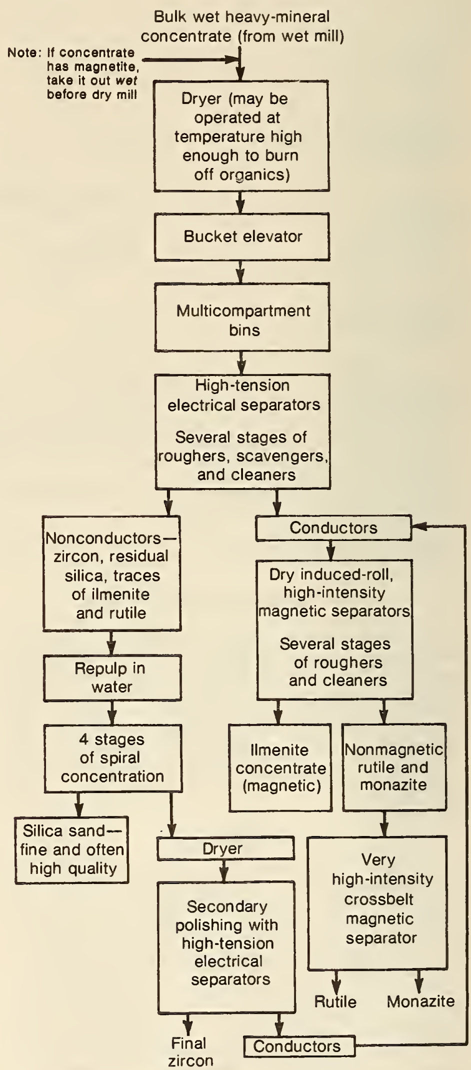

Figure 8.—Generalized flowsheet of a mineral sand wet mill.

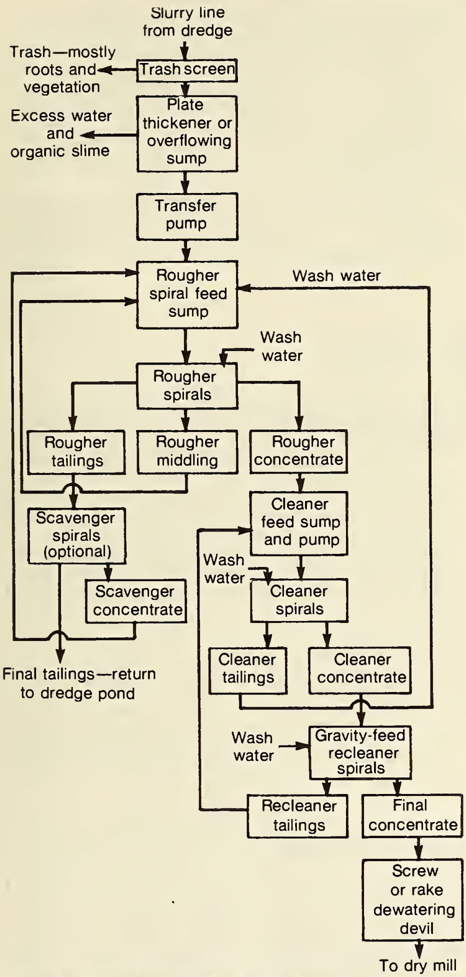

Figure 9.—Generalized flowsheet of a mineral sand dry mill.

solids to the wet mill where it is fed into one or more stages of gravity concentrators, producing a preliminary heavy-mineral concentrate. Wet mills can be land based or floating, depending on the condition required at the deposit. Rough, heavy-mineral concentrate from the wet mill is transported, usually by truck or barge, to the dry mill for further separation and concentration. The specific flowsheet of a dry mill depends considerably on the type of ore and heavy-mineral assemblage to be recovered. Dry mills use various stages of high-tension electrical separation, induced-roll magnetic separation, and additional gravity separation methods to produce specific titanium raw material (ilmenite, rutile) and other heavy-mineral concentrates (zircon, monazite). A general flowsheet would consist primarily of high-tension electrical separators to separate conductors (ilmenite, rutile, monazite) from nonconductors (zircon). The conductors are further separated using both dry, induced-roll, high-intensity magnetic separators and very high-intensity crossbelt magnetic separators, into the ilmenite, rutile, and monazite concentrates. The nonconductors use various stages of spiral concentration and high-tension electrical separators to separate the zircon concentrate from the residual silica sand. Variations to typical wet and dry mill procedures are used throughout the world based on the composition and type of mineral sand.

Three nonproducing hard-rock deposits—one each in Brazil, Canada, and the United States—have proposed operations that would use gravity and/or magnetic and high-intensity electrical separation methods to recover titanium concentrate. Operations such as the MacIntyre Development in New York, the Tellnes ilmenite mine in Norway, the Otanmaki Mine in Finland, and the Piampaludo deposit in Italy use or would use flotation methods to recover titanium raw materials. At Tellnes, the coarser part of the ilmenite is being recovered by gravity separation. Ore is processed through various stages of crushing, grinding, and wet or dry magnetic separation, to remove any tramp iron, magnetite, and garnet; it is then deslimed, thickened, scrubbed, and conditioned prior to flotation. Most operations have one or two flotation circuits; large operations use more circuits to remove various minerals such as pyrite, pyroxene, and remaining garnet, and apatite. Operations such as Tellnes and a proposed Brazilian operation (Catalao) leach the flotation concentrate to remove apatite. In other operations, the flotation concentrate is processed through high-intensity magnetic separators to separate the titanium raw materials of ilmenite-anatase or ilmenite-rutile.

All the recovered titanium concentrates from either wet or dry mill or flotation processes are for pigment production using either the chloride process or the sulfate process. In addition, ilmenite can be used in the production of titanium slag or synthetic rutile.

UPGRADED ILMENITE-SYNTHETIC RUTILE

The abundance of ilmenite and scarcity of rutile has led to the research and development of processes for upgrading ilmenite to a low-iron, high-titanium (90 to 97 pct TiO_2) product called synthetic rutile. Most upgrading processes fall into four major groups: direct oxidation often followed by reduction and acid leaching, a pyrometallurgical method, a carbonyl process, and direct acid leaching methods.

A commonly used ilmenite upgrading process is direct oxidation-reduction followed by "rusting" and acid leaching. This is often referred to as the "Western Titanium"[7] process. The Australian and Indian synthetic rutile is produced in this manner. After the oxidation of ilmenite, the iron oxide content is reduced to metallic iron in a rotary kiln with the addition of coal. The metallic iron is removed by agitating the reduced ilmenite in aerated water (which is slightly acidic) so that the iron oxide "rusts away" from the ilmenite. The precipitated iron oxide is then separated from the upgraded ilmenite, and the final product is leached in acid (*13*). A 93-pct-TiO_2 product is produced by this process.

Another significant synthetic rutile process is that practiced by Kerr-McGee Chemical Corp. at its Mobile, AL,

[7]Developed by Western Titanium Ltd., Western Australia.

facility. The Kerr-McGee process is a modification of the benelite cyclic process. The basic steps include a reduction roast of the ilmenite ore followed by a hydrochloric acid pressure leach. In this process, a 95-pct-TiO_2 product is produced (*14*).

The Bureau has researched three different upgrading methods—a pyrometallurgical process, a carbonyl process, and a direct acid leaching process. In the pyrometallurgical process, low-iron, high-titanium ilmenite concentrate is blended with coke and lime, then smelted in electric arc furnaces, producing a salable pig iron and a titanium slag. The slag is treated with oxygen and titanium pyrophosphate, which converts titanium oxides to crystalline rutile and produces a phosphate glass containing most of the impurities. Following this step, the rutilized slag is leached with dilute sulfuric acid and filtered to extract the synthetic rutile product containing approximately 92 pct TiO_2 (*15*).

In the carbonyl process, an ilmenite concentrate is first reduced, converting iron oxides to metallic iron, then treated with carbon monoxide at high temperatures and high pressures. This converts the metallic iron to iron pentacarbonyl, which appears as liquid or vapor and is removed by gravity flow and vapor transport. The synthetic rutile product, having a rutile crystal structure, is suitable for chlorination (*16*).

In 1970, the Bureau of Mines investigated the use of direct acid leaching methods to convert ilmenite to rutile substitutes. The best results appear to be processes that employ hydrochloric and sulfuric acids (*17*).

GEOLOGY AND RESOURCES

Estimates of demonstrated titanium resources throughout the world in the deposits studied are 438 million mt of contained TiO_2 (table 6, fig. 10). Although Australia has the largest share of demonstrated ore resources (42 pct of the world total), these low-grade beach-sand-type deposits account for only a small share (11 pct) of the total contained TiO_2 in the demonstrated resources. Nevertheless, Australia's mines and deposits account for a large share of current world production of titanium concentrates (at 37 pct for ilmenite and 64 pct for rutile).

Regionally, titanium resources are widespread, with North America and Europe accounting for over 50 pct of the contained TiO_2 in the deposits included in this study. Table 6 also shows the large potential of anatase resources located in Brazil.

From the 63 deposits studied, additional resources of at least 314 million mt of contained TiO_2 are estimated to exist at the inferred level. The majority of this is located in Australia and New Zealand (41 pct), Brazil (18 pct), India (14 pct), and the Republic of South Africa (13 pct). The remainder is found in the United States, Canada, Finland, Italy, and Sierra Leone. These inferred resources represent an increase of over 70 pct from the demonstrated amount.

Table 6.—Summary of identified titanium resources[1] in market economy countries, January 1984

	Ore-sand, 10^6 mt		Contained TiO_2, 10^6 mt		Av TiO_2 grade,[3] wt pct	Source,[4] pct	
	Demonstrated	Inferred	Demonstrated	Inferred[2]		Hard rock	Placer
NORTH AMERICA							
United States:							
Rutile			1.5	0	0.24	12	88
Ilmenite	1,726	223	39.8	8.9	2.32	58	42
Leucoxene			1.0	0	.15	0	100
Canada: Ilmenite	238	114	72.5	8.8	30.50	100	0
Total or average, North America	1,963	337	114.8	17.7	5.85	83	17
SOUTH AMERICA							
Brazil:							
Anatase			75.5	37.0	19.68	100	0
Rutile	526	670	.1	.5	.11	0	100
Ilmenite			17.8	19.4	12.58	91	9
Total or average, South America	526	670	93.4	56.9	17.75	98	2
EUROPE							
Finland: Ilmenite	11	19	1.4	.2.6	13.50	100	0
Italy:							
Rutile			20.7	17.5	4.37	100	0
Ilmenite	473	400	8.5	7.2	1.79	100	0
Norway: Ilmenite	497	0	89.4	0	18.00	100	0
Total or average, Europe	981	419	120.00	27.3	12.23	100	0
ASIA							
India:							
Rutile			4.3	2.4	0.88	0	100
Ilmenite	487	455	30.2	41.6	6.20	0	100
Leucoxene			.6	0	.27	0	100
Sri Lanka:							
Rutile			.8	0	1.17	0	100
Ilmenite	65	0	3.7	0	5.69	0	100
Total or average, Asia	552	455	39.6	44.0	7.17	0	100

See footnotes at end of table.

Table 6.—Summary of identified titanium resources[1] in market economy countries, January 1984—Continued

	Ore-sand, 10^6 mt		Contained TiO_2, 10^6 mt		Av TiO_2 grade,[3] wt pct	Source,[4] pct	
	Demonstrated	Inferred	Demonstrated	Inferred[2]		Hard rock	Placer
AFRICA							
Sierra Leone: Rutile	129	17	2.1	0.3	1.61	0	100
South Africa, Republic of:							
Rutile	685	1,538	2.3	5.1	.33	0	100
Ilmenite			15.6	35.1	2.28	0	100
Total or average, Africa	814	1,555	20.0	40.5	2.46	0	100
OCEANIA							
Australia (east coast):							
Rutile	3,007	1,461	7.2	4.7	0.24	0	100
Ilmenite			12.0	4.4	.40	0	100
Australia (west coast):							
Rutile	546	813	2.8	2.8	.56	0	100
Ilmenite			22.7	70.9	4.16	18	82
Leucoxene			1.9	1.8	.37	0	100
New Zealand:							
Rutile	73	924	.1	.9	.09	0	100
Ilmenite			3.4	42.5	4.60	0	100
Total or average, Oceania	3,626	3,198	50.1	128.0	1.38	8	92
Grand total or average	8,462	6,634	437.9	314.4	5.17	71	29

[1]Representing only those mines and deposits included in this study.
[2]Inferred contained TiO_2 tonnage is not necessarily based on the listed demonstrated grade and therefore cannot be calculated from the average TiO_2 grade.
[3]Represents demonstrated level resource grade. The total average TiO_2 grade for each region is a weighted average of all titanium minerals from that region.
[4]Based on the contained demonstrated level tonnage.

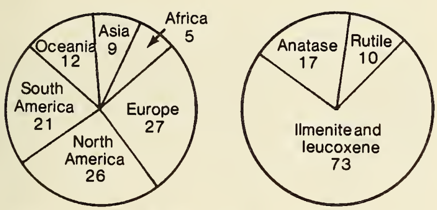

Figure 10.—World titanium resources, by region and type. (Total = 438 million mt of contained TiO_2.) Numbers within pies refer to percent of total resources.

In 1973, the U.S. Geological Survey reported that nearly 2 billion mt of contained titanium existed in the world at the identified resource level (demonstrated plus inferred), with approximately 15 pct in the United States, and there may be an additional 1.5 billion mt of contained titanium in hypothetical resources in the world (*18*). Both of these values have recently been updated by the Geological Survey's titanium specialist and are discussed in appendix A (*2*).

The economic titanium minerals ilmenite, rutile, and anatase, and the possibly economic mineral perovskite, occur in a variety of different deposit types. These include several types in hard rocks (igneous gabbro-anorthosite assemblages, alkalic igneous rocks, unusual metamorphic rocks), weathered and hydrothermally altered rocks, and placer deposits.

Gabbro-anorthosite assemblages, typically of Precambrian age, commonly contain ilmenite (locally with rutile) disseminated and/or as massive segregations. Intergrowths with magnetite are a major problem. Major deposits are in Norway, Canada, and the United States.

Alkalic igneous rocks (of any age) may contain rutile, anatase, or perovskite, all commonly with chemical impurities. Alteration by weathering may produce a more attractive ore, as in Brazil.

Metamorphic rocks of eclogite facies contain rutile and are important resources in Italy and the U.S.S.R. Aluminous metamorphic rocks and hydrothermally altered rocks contain large low-grade resources of rutile.

The rock-hosted deposit types in the United States have collectively been estimated to contain 67 million mt TiO_2 by the Geological Survey and Bureau titanium specialists (*2*). (Their estimates include low-grade resources and a larger number of deposits than this study.)

Placer deposits of titanium minerals include shoreline-complex sands of modern and former shorelines and fluvial placers. Shoreline-complex sands, which contain the more important resources, include beach deposits, aeolian (dune) deposits, and other related sand deposits. Any titanium mineral resistant to abrasion and weathering, such as rutile and ilmenite (or formed by weathering such as altered ilmenite), may be concentrated along with other resistant heavy minerals such as zircon and monazite, in the manner commonly observed on many beaches. These deposits may be of any age, but most resources are present in Tertiary to modern deposits with relict depositional topography. Important deposits are in Australia, South Africa, and the United States. Placer deposits in the United States have been estimated (*2*) to contain 49 million mt of TiO_2.

TITANIUM DEPOSIT COSTS

COSTING METHODOLOGY

For each property included in this study, a cost evaluation was made for both capital and operating costs, to reflect, as nearly as possible, actual operations, or in the case of nonproducing sites, expected operational technologies and capacities. Costs for the deposits in the United States were developed by Bureau Field Operations Centers in Pittsburgh, PA, and Denver, CO, based on actual reported company data, scaling from similar known operations, or using the cost estimating system (CES) (*19*). Costs from all foreign deposits were collected and developed by Kaiser Engineers, Inc., under a contract with the Bureau. Some of the foreign deposit costs are actual company-reported data; others were estimated by Kaiser Engineers, using the contractor's knowledge of the operation or deposit plus experience in the industry. The costs for Australia were modeled by the contractor based on actual Australian heavy-mineral operation's costs.

All costs presented in this report are in terms of January 1984 U.S. dollars. The cost estimates should be accurate to within ±25 pct, which reflects standard industry prefeasibility estimates.

Capital expenditures were calculated for exploration, acquisition, development, mine plant and equipment, construction of the mill plant, and installation of the mill equipment. Capital expenditures for mining and processing facilities include the costs of mobile and stationary equipment, engineering design, facilities and utilities, and working capital. Facilities and utilities (infrastructure) include the cost of access and haulage facilities, water facilities, power supply, and personnel accommodations. Working capital is a revolving cash fund required for such operating expenses as labor, supplies, taxes, and insurance.

Mine and mill operating costs are a combination of direct and indirect costs. Direct operating costs include materials, utilities, direct and maintenance labor, and payroll overhead. Indirect operating costs include technical and clerical labor, administrative costs, facilities maintenance and supplies, and research. Other costs in the analysis are fixed charges that include local taxes and insurance.

When applicable, the mill operating cost includes the cost of both the wet and dry mill. In addition, synthetic rutile plant or titanium slag smelter operating and capital costs are included where applicable.

OPERATING COSTS

Table 7 lists the average operating costs for selected titanium operations (expressed as dollars per metric ton of titanium concentrate). The costs for titanium operations in other countries are not represented on the table because of the limited numbers of deposits in those countries, to protect confidentiality. For primary rutile operations, the mine operating cost primarily represents the cost of dredging and the wet mill (particularly for Australia). For the producers in Australia, this cost is nearly $200/mt, while in India and Sri Lanka it is only one-quarter of that. The mine costs in India and Sri Lanka are considerably less than in Australia because mining is very labor intensive (in India, mining is done by hand-shoveling). The mine cost increases to nearly $300/mt for the nonproducers (in Australia), primarily owing to the lower ore grades. The mill costs for

Table 7.—Estimated average operating costs for selected titanium mines and deposits[1]

(January 1984 U.S. dollars per metric ton of product on a weight-average basis)

	Mine	Mill	Other[2]	Transportation to plant or market[3]	Total
Primary rutile (natural):					
Australia:					
Producers	$195	$100	$49	$6	$350
Nonproducers	286	125	168	24	603
India and Sri Lanka:					
Producers	48	91	173	18	330
Primary ilmenite:					
Australia:					
Producers	12	9	4	2	27
Nonproducers	41	19	21	17	98
United States, Finland, and Norway: Producers	10	18	4	4	36

NAp Not applicable.

[1]The costs are expressed in terms of dollars per metric ton of titanium concentrate, whichever is appropriate (i.e., the costs for primary rutile mines in Australia would be in terms of dollars per metric ton of rutile concentrate).

[2]Includes all property, State, Federal, and severance taxes, plus any royalty. Nonproducers would require higher income in order to provide the stipulated 15-pct DCFROR, thus aggregate tax payments are generally higher than for producing operations.

[3]Cost represents the transportation cost to pigment plant or local port or market.

the primary rutile operations represent primarily the dry mill. For producers, this cost averages $90/mt to $100/mt in both Australia and India and Sri Lanka, and only increases to $125/mt for the nonproducers (in Australia). The costs labeled "other" include all property, State, Federal, and severance taxes, plus royalties, if any. Taxes are generally greater for nonproducers in this study, because, in most cases, the revenues required to cover the higher overall costs (including profit) are greater. In other words, nonproducers would require a higher taxable income (leading to higher tax payments) in order to cover all operating costs and provide for a 15-pct DCFROR on all investments. The high cost listed under "other" for the Indian and Sri Lankan rutile producers is due to the high Federal corporate income tax rate in those countries. The total operating costs shown on table 7 for primary rutile producers range from a low of $330/mt in India and Sri Lanka to a high of $350/mt for mines in Australia. These compare closely with the average market price of rutile in 1984 of $350/mt. The Australian nonproducing rutile deposits have an average total cost of just over $600/mt, considerably higher than the 1984 market price.

The mine cost for primary ilmenite mines (producers) averages $11/mt in Australia, the United States, Finland, and Norway, and increases to about $40/mt for the nonproducers in Australia (where the ore grade is lower). The mill cost for the producers in the United States, Finland, and Norway is twice that of Australia ($18/mt versus $9/mt). This represents the higher cost of processing hard-rock ore as opposed to the ore from beach sand deposits. The total operating cost for primary ilmenite producers in Australia is nearly $10/mt less than for the producers in the United States, Finland, and Norway. This compares well with the $10/mt differential in market prices for ilmenite in Australia (at $32/mt) versus the United States (at $42/mt). The total operating cost for the primary ilmenite nonproducers (in Australia) is almost four times

that of the producers, owing primarily to the lower grades at the nonproducing deposits.

A representative synthetic rutile operating cost is just over $280/mt product, on the average, for both Australian and Indian plants. Since nearly 2 mt of ilmenite concentrate, at approximately $30/mt to $40/mt of product (depending on market location), is necessary to produce 1 mt of synthetic rutile, the cost to produce synthetic rutile is comparable to that of producing natural rutile ($70 + $280 = $350/mt). The 1984 market prices for rutile and synthetic rutile are $350/mt and $340/mt, respectively.

CAPITAL COSTS

Table 8 shows average capital costs estimated for this study to develop nonproducing surface deposits in Australia, in terms of U.S. dollars. Only Austraiia was used because no other regions of the world have enough nonproducing deposits to be included separately without compromising the confidentiality of individual deposit data. Costs represent acquisition, exploration, development, and equipping a new mine site, along with construction of any mine and mill plants and buildings necessary (wet and dry mills). Mine costs, mainly for the dredge and floating wet mill, are greater than the mill costs, which mainly represent the dry mill.

Table 8.—Estimated capital costs to develop nonproducing surface titanium deposits in Australia

(Thousand January 1984 U.S. dollars)

Capacity, 10^3 mt/yr ore feed	3,400	15,800
Exploration, acquisition, and development	$4,300	$7,700
Mine	8,600	22,600
Mill	6,300	16,100
Total	19,200	46,400

TYPICAL BEACH SAND MINING COSTS—AUSTRALIAN DEPOSITS

Nearly two-thirds of the mines and deposits included in this study produce or are proposed to produce beach-sand-type ores. In most of these operations, standard beach sand mining technologies are applied, which typically include dredging or dry surface mining plus wet and dry milling. Australia is by far the leader in the field of beach sand mining; therefore, costs for its operations are representative of typical beach sand production costs, when financial differences from one region of the world to another are not taken into account.

The costs presented in this section were estimated based on known Australian operations. Costs were originally estimated in 1981 Australian dollars, updated to 1984 Australian dollars, then converted to 1984 U.S. dollars using the appropriate exchange rate. In most cases, the costs were estimated for 500-, 1,000-, 1,500-, and 2,000-mt/h dredges and wet mills, and 15-, 30-, 45-, and 60-mt/h dry mills. In nearly all cases, these operations were assumed to run three shifts per day, 300 d/yr (or 7,200 h/yr).

Figures 11 and 12 show capital costs for the dredge, wet mill, and dry mill. The dredge cost represents the cost to buy and construct the dredge including the floatline. This capital cost ranges from just over $500,000 for dredges with a 500-mt/h capacity up to $2.6 million for dredges with a

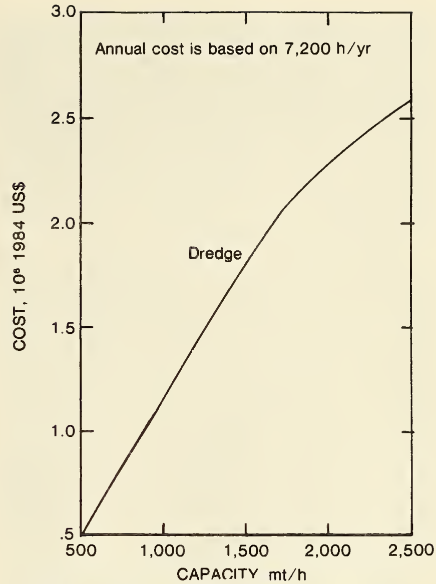

Figure 11.—Capital costs for a dredge, Australia.

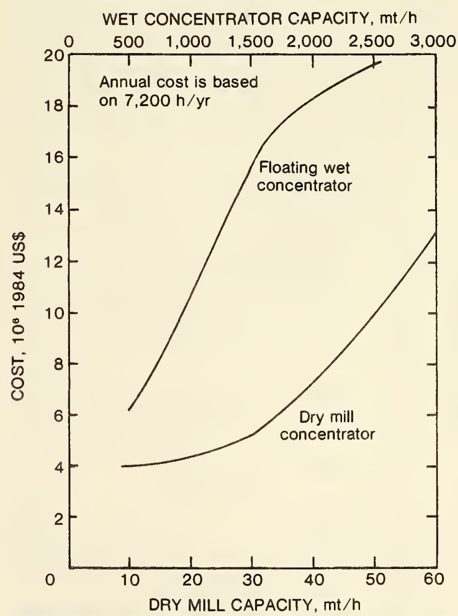

Figure 12.—Capital costs for wet and dry mill concentrators, Australia.

2,500-mt/h capacity. The data indicate a slight economy of scale for the higher capacity dredges. The costs for the floating wet mill represent the costs to construct and equip the floating wet concentrator, typically with cones. The capital costs range from $6.2 million for a 500-mt/h mill to just over $18 million for a 2,000-mt/h mill. A slight economy of scale seems to occur for the higher capacity mills. Costs for the dry mill, in addition to the magnetite and electrostatic circuits, include costs to equip and construct the feed preparation section, service buildings, and product bins (for truck loading) or feed conveyors (for rail loading). The costs range from just over $4 million for a 15-mt/h mill to $13.5 million for a 60-mt/h mill.

Figure 13 shows the annual operating costs for dry mining (contractor operated). These curves depict the costs for three operations: bulldozer and sluicing, scraper with dozer (for hauls of 0.75 km or less), or front-end loader (FEL) and truck haulage (for hauls up to 2.5 km). Bucket wheel excavators and a conveyor (for large amounts of tonnage and long hauls) would be a fourth option, but there were insufficient data points to construct a curve. Bulldozer-sluicing costs range from approximately $750,000/yr for a 600-mt/h operation to nearly $2 million per year for an 1,800-mt/h operation. Scraper-dozer costs range from $1.8 million per year for a 600-mt/h operation to $4.7 million per year for an 1,800-mt/h operation. Costs for FEL-truck operations range from over $3 million per year for a 600-mt/h operation to nearly $6.7 million per year for the 1,800-mt/h operation. The curves exhibit some economy of scale, especially at the higher capacities.

Figure 14 shows curves depicting the annual cost of operating a dredge (for wet mining), a floating wet mill, and a dry mill. A cable dredge was assumed more effective at lower capacities and a walking (pontoon) dredge at higher capacities. Costs for the dredge range from just over $400,000/yr for a 500-mt/h operation to over $1.3 million per year for a 2,000-mt/h operation. Labor costs account for approximately 17 pct of the total annual dredging cost; fuel and electricity (with electricity being the far greater cost) account for almost 35 pct; and parts plus maintenance labor account for 48 pct. Floating wet mill costs range from nearly $2.4 million per year for a 500-mt/h operation to over $3.5 million per year for a 2,000-mt/h operation. Labor costs account for 54 pct, electricity for 15 pct, and parts, maintenance labor, and water supply for the remaining 31 pct of the total annual wet mill costs. Dry mill costs range from over $1.5 million per year for a 15-mt/h operation to approximately $2.8 million per year for a 60-mt/h operation. Labor costs at the dry mill also account for 54 pct of the total annual operating costs; electricity and fuel account for 28 pct; and the remaining 18 pct is for parts and maintenance labor. The only curve that exhibits any significant economy of scale is that of the floating wet mill, at its higher capacities.

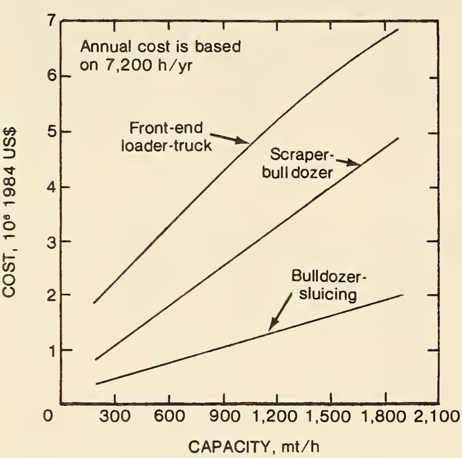

Figure 13.—Annual operating costs for dry mining operations, Australia.

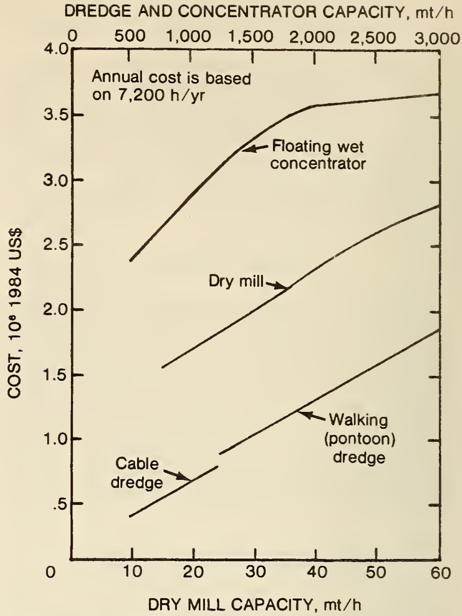

Figure 14.—Annual operating costs for dredge and wet and dry mill concentrators, Australia.

Labor costs for all of the curves are based on an annual average wage scale in Australia (U.S. dollars) of approximately $23,000/yr per person (including 50 pct overhead). This cost is based on Queensland Award Rates for mineral sands mining operations. For operations in other States, a factor was applied to convert this rate. The total number of people employed to operate the equipment ranged from 4 to 8 persons per year on the dredge, 60 to 80 persons in the wet mill, and 45 to 55 persons in the dry mill. The ranges reflect the various sizes of the operations.

Power costs range from 2.7¢/kW•h to 3.6¢/kW•h in Queensland (in U.S. dollars), and these rates are also applicable to the other States of Australia where mineral sand operations exist. With the exception of the dry mill, fuel costs are nonexistent or very small. Fuel costs at the dry mill are based on just over 30 US¢L.

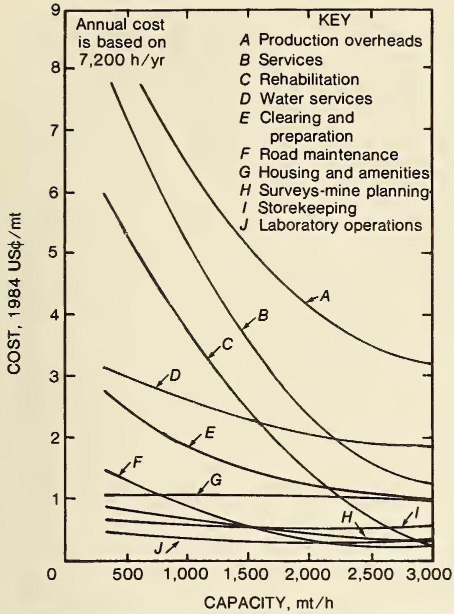

Figure 15.—General costs associated with beach sand mining operations, Australia.

The last set of curves (fig. 15) identifies all of the general costs not directly associated with the mining and milling operation in particular. Curves are represented for clearing and preparation, rehabilitation, services, water services, road maintenance, housing and amenities, production overheads, storekeeping, surveys and mine planning, and laboratory costs. The costs on these curves are presented in terms of cents per metric ton ore.

TITANIUM CONCENTRATE AVAILABILITY

ECONOMIC EVALUATION METHODOLOGY

Once all of the cost and engineering data are established, production parameters and cost estimates for each mine and deposit are entered into the supply analysis model (SAM). The Bureau has developed the SAM to perform discounted-cash-flow rate of return (DCFROR) analyses to determine the long-run constant dollar price at which the primary commodity must be sold to recover all costs of production and investments (*20*). The DCFROR is most commonly defined as the rate of return that makes the present worth of cash flow from an investment equal to the present worth of all after-tax investments (*21*). For this study, a 15-pct DCFROR is considered the necessary rate of return to cover the opportunity cost of capital plus risk. The determined value for the primary commodity price is equivalent to the average total cost of production (including credits for byproducts) for the operation over its producing life, under the set of assumptions and conditions necessary to make an evaluation (e.g., mine plan, full capacity production, and a market for all output).

If an operation has more than one product, the prices of the byproducts are assumed to be the market prices for the period of analysis, which for this study is January 1984. Revenues generated from byproducts are credited against the costs of production. Market prices used in this analysis are shown in table 9. No revenues were generated for byproduct ilmenite, when assumed to be stockpiled.

Table 9.—Market prices of titanium concentrates and related minerals for January 1984 (*22-24*)

Commodity	Where applicable (f.o.b.)	Grade, pct	Price, $/mt
Titanium product:			
Ilmenite concentrate	Mill, Australia	[1]54 + TiO_2	$32.00
Do	Mill, United States	[1]54 + TiO_2	42.00
Leucoxene concentrate.	Mill, Western Australia	87 TiO_2	225.00
Rutile concentrate	Mill	95 TiO_2	347.00
Synthetic rutile	Plant, Mobile, AL, United States	90 + TiO_2	350.00
Titanium slag	Sorel, Quebec, Canada	71 TiO_2	159.00
Do	Richards Bay, Republic of South Africa	85 TiO_2	181.00
Byproduct:			
Garnet	Mill	Abrasive	10.00
Magnetite	..do	NAp	23.00
Monazite concentrate	..do	55 REO	389.00
Pig iron	..do	NAp	235.66
Zircon concentrate	Mill, Australia	65 ZrO_2	104.50
Do	Mill, United States	65 ZrO_2	182.00

[1]Price does vary on TiO_2 grade (from ~47 to ~64 pct TiO_2). This also applies to the values listed in the text.

If an operation has more than one *titanium* product, a "primary" product is selected on which to run the price determination. The primary product is defined as the titanium product that generates the greatest revenues. All other products are assumed to be the byproducts.

Based on the methodology for this study, all capital investments incurred earlier than 15 yr before the initial year of the analysis (January 1984) are treated as depreciated costs. Capital investments incurred less than 15 yr before January 1984 have the estimated undepreciated balance carried forward to January 1984, with all subsequent investments reported in constant January 1984 dollars. All reinvestment, operating, and transportation costs are updated, by computer, to January 1984 U.S. dollars using country economic indexes.

The SAM contains a separate tax records file for each State or nation, which includes all the relevant tax parameters such as corporate income taxes, property taxes, royalties, severance taxes, or other taxes under which a mining firm would operate. These tax parameters are applied against each mineral deposit under evaluation with the implicit assumption that each deposit represents a separate corporate entity.

Other items that may be considered in the analysis, if they are allowed in the specific country, include depreciation, depletion, deferred expenses, investment tax credits, and tax loss carryforwards.

Detailed cash-flow analyses are generated by the SAM for each preproduction and production year of an operation, beginning with the initial year of the analysis, 1984. Upon completion of the individual property analyses for each mine and deposit, all properties included in the study were simultaneously analyzed and the data were aggregated into resource availability curves. Two types of curves have been generated for this study: (1) total availability curves and (2) annual curves at selected production costs. Costs reflect not only capital and operating costs, but also all pertinent taxation and the cost of transporting the product to the nearest port or point of consumption.

The total resource availability curve is a tonnage-cost relationship that shows the total quantity of recoverable primary product (titanium concentrate) potentially available at each operation's average total cost of production (less byproduct credits) over the life of the mine, determined at the stipulated (15-pct) DCFROR. Thus, the curve is an aggregation of the total potential quantity of titanium concentrate that could be produced over the entire producing life of each operation, ordered from operations with the lowest average total cost of production to those with the highest. The curve provides a concise, easy-to-read, graphic analysis of the comparative costs associated with any given level of potential output and provides an estimate of what the average long-run price of the titanium concentrate (in January 1984 dollars) would likely have to be in order for a given tonnage to be potentially available to the marketplace. For this study, separate discussions and curves were generated for each titanium concentrate (rutile and ilmenite) in order to correctly represent the various titanium concentrate availabilities.

Annual curves are simply disaggregations of the total curves to show annual titanium availability at varying costs of production. Each curve represents a specific cost level. The horizontal axis represents time, either actual years (for producers) or the number of years following the commencement of development (for nonproducing operations). The vertical axis represents the annual production level based upon aggregation of the proposed production levels of each individual property.

Certain assumptions are inherent in all the curves. First, all deposits produce at full operating capacity throughout the productive life of the deposit. Second, each operation is able to sell all of its byproducts at the stipulated prices and all of its primary product at a price sufficient to generate total revenues at least equal to its average total production cost. Third, development of each nonproducing deposit began in the same base year (N) (unless the property was developing at the time of the evaluation). Since it is difficult to predict when the explored deposits are going to be developed, this assumption was necessary in order to illustrate the maximum potential availability with a minimum lag time. It is doubtful, however, that this potential would be reached in the short term since it is unlikely that all new producers would start preproduction in the same year. The preproduction period allows for only the minimum engineering and construction period necessary to initiate production under the proposed development plan. Consequently, the additional time lags and potential costs involved in filing environmental impact statements, receiving required permits, financing, etc., have not been included in the deposit analyses.

TOTAL AVAILABILITY

Rutile

The 40 deposits containing rutile that are analyzed in this study contain 29.2 million mt of recoverable rutile concentrates, with an average grade of 95 pct TiO_2 (table 10). These resources are either the primary product of rutile

Table 10.—Total estimated recoverable rutile concentrates, as of January 1984

(Thousand metric tons of product)

	Australia	Brazil, Italy	India, Sri Lanka	Sierra Leone, Republic of South Africa	United States	Total
As primary-product rutile:						
Producers	3,270	0	2,837	1,544	169	7,820
Nonproducers	4,257	12,081	0	0	713	17,051
Total	7,527	12,081	2,837	1,544	882	24,871
As a coproduct from ilmenite:						
Producers	1,136	39	866	1,556	0	3,597
Nonproducers	461	0	0	0	313	774
Total	1,597	39	866	1,556	313	4,371
Grand total	9,124	12,120	3,703	3,100	1,195	29,242

mines or occur as a coproduct from mines producing ilmenite. Rutile resources available as a primary product are 24.9 million mt, 85 pct of the total.

Estimated recoverable rutile resources located in Australia are over 9 million mt, or 31 pct of the total recoverable rutile contained in deposits analyzed in this study. Rutile potentially recoverable from producing mines in Australia is 4.4 million mt, about 39 pct of rutile concentrates estimated to be recoverable from all producing rutile mines included in this study. Recoverable rutile concentrates from Australian nonproducing deposits are over 4 million mt, more than a quarter of the estimated rutile recoverable from all nonproducing rutile deposits.

Rutile concentrates recoverable from mines and deposits located in India and Sri Lanka are almost 4 million mt; this is almost 13 pct of the total. Rutile concentrates located in the United States are about 1.2 million mt or only 4 pct of the total. Other countries with deposits containing recoverable rutile concentrates are Sierra Leone, the Republic of South Africa, Brazil, and Italy. The Italian Piampaludo deposit has the largest future potential of all the nonproducing deposits represented on the table.

The total availability curve for rutile concentrates from deposits containing rutile as the major product or as an important coproduct is shown in figure 16*A*. This curve shows that about 10.8 million mt of rutile concentrate, 37 pct of the total estimated recoverable rutile concentrate, can be produced at a cost that is less than the January 1984 market price of $347/mt, f.o.b. mill. An additional 14.5 million mt is available at costs up to double the market price. The tonnage available at costs of less than $700/mt represents 87 pct of the total resource. The curve does include a very small tonnage of rutile associated as a byproduct from ilmenite operations (3.5 pct).

Because Australia is a major world producer of rutile concentrates, accounting for 64 pct of world production in 1981, a separate resource cost curve, figure 16*B*, is presented for mines and deposits in Australia. The total amount of rutile concentrate potentially recoverable from Australian deposits is about 9.1 million mt; almost 52 pct of this, 4.7 million mt, is potentially available at a cost of production of less than $347/mt. (The curve does not include a small quantity of rutile associated with costs greater than $1,200/mt.)

The United States has only a small amount of its total rutile resource of 1.2 million mt available at costs less than the January 1984 market price. This is associated with the only producing primary-product rutile mine in the United States in 1984.

The tonnage of rutile concentrates potentially recoverable from producing mines for which rutile was the primary product or a major coproduct is shown on figure 16*C*. The total rutile recoverable from producing mines is over 11.4 million mt of rutile concentrate, only 39 pct of the total

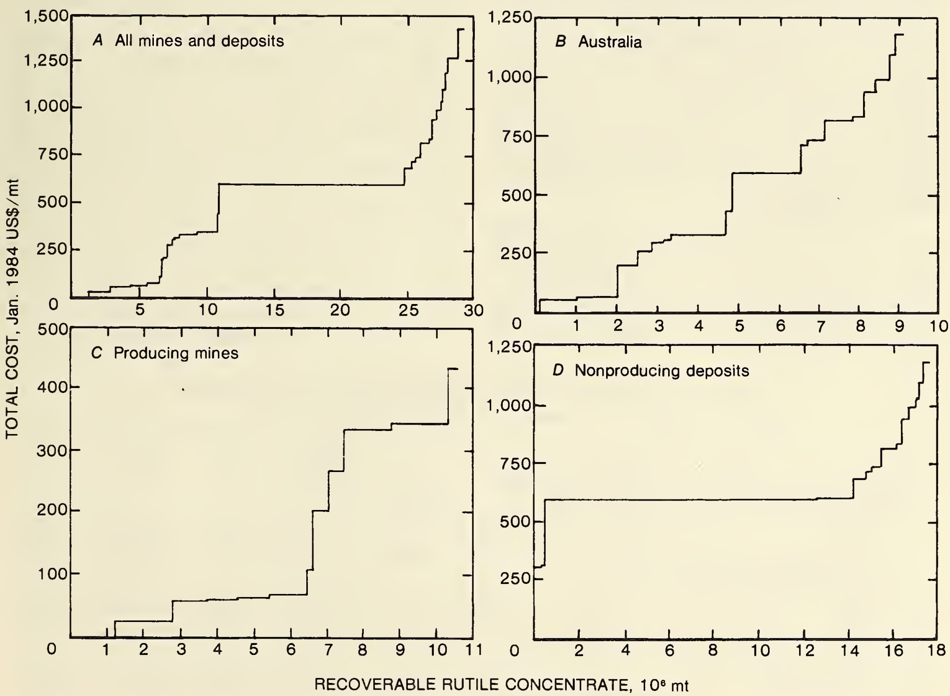

Figure 16.—Total recoverable rutile concentrate.

potentially recoverable from all rutile mines. (The curve in figure 16*C* shows less than 11.4 million mt because it does not include a small quantity of byproduct rutile available at costs greater than $450/mt.) About 10.3 million mt, 90 pct, is potentially available at costs less than $347/mt.

The total rutile cost-tonnage relationship for nonproducing deposits is illustrated in figure 16*D*. Resources associated with nonproducing deposits were almost 18 million mt, almost 61 pct of all rutile potentially available. (The curve does not include a small quantity of rutile associated with costs greater than $1,200/mt.) Approximately 500,000 mt was potentially available at a cost of less than the current market price, primarily from deposits located in restricted areas in Australia, such as national parks.

This study shows that the majority of low-cost rutile is contained in Australian deposits. It also demonstrates that there is only a small quantity of low-cost rutile that was not being produced in 1984. Later sections will discuss potential substitutes for rutile in the future, such as anatase and synthetic rutile.

Ilmenite

It is estimated that 246 million mt of ilmenite, containing typically 54 pct TiO_2, could be recovered from the demonstrated resources of 17 primary-product ilmenite mines and deposits, 23 primary-product rutile mines and deposits, and 3 mines that feed synthetic rutile operations (table 11). This demonstrates an abundance of ilmenite resources based on a 1981 world production level of 3.6 million mt/yr. This analysis assumed that for many potential byproduct sources the ilmenite would be stockpiled rather than sold. Resources of ilmenite that were selected as being a part of a stockpile are those that are presently being stockpiled or would likely be stockpiled. Most often these stockpiles of ilmenite are or would be high in chromium content and therefore not a desirable product. Most of these resources are located in Australia. This tonnage was part of the ilmenite resources, but no revenues from the sale of ilmenite were credited.

Resources associated with primary-product ilmenite mines account for approximately 72 pct of the total recoverable ilmenite concentrate. Ilmenite resources located in Europe contain by far the greatest portion of all primary-product ilmenite potentially recoverable (76 pct). Ilmenite potentially recoverable from primary-product ilmenite operations located in the United States and Australia is 24 million mt and 17 million mt, 13 pct and 10 pct of the total, respectively.

The total recoverable ilmenite from primary ilmenite deposits is shown in figure 17*A*. (The total quantity shown is less than 178 million mt because the curve does not include ilmenite associated with costs greater than $200/mt.) The curve shows that over 145 million mt of ilmenite concentrate is potentially recoverable, primarily from European deposits, at a cost less than the January 1984 U.S. cost of $42/mt. This is over 81 pct of the total primary ilmenite potentially available.

Primary ilmenite resources located in Austrlia that can potentially be recovered at a cost less than the January 1984 Australian market price of $32/mt are over 10 million mt.

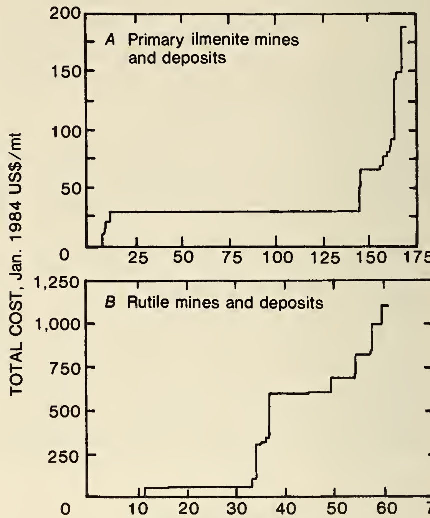

Figure 17.—Total recoverable ilmenite concentrate.

Table 11.—Total estimated recoverable ilmenite concentrates, as of January 1984

(Thousand metric tons of product)

	Australia	Brazil	India, Sri Lanka	Italy, Finland, Norway	United States	Total
As primary-product ilmenite:						
Producers	10,015	2,343	0	134,929	[1]0	147,287
Nonproducers	7,019	0	0	0	23,694	30,713
Total	17,034	2,343	0	134,929	23,694	178,000
As a byproduct or coproduct with rutile:						
Producers	5,764	0	28,289	0	610	34,663
Nonproducers	12,925	0	0	8,101	4,829	25,855
Total	18,689	0	28,289	8,101	5,439	60,518
As a byproduct or coproduct with ilmenite used for synthetic rutile: Producers	5,286	0	2,119	0	0	7,405
Grand total	41,009	2,343	30,408	143,030	29,133	245,923

[1]Included as either a "mixed" product or as a byproduct from ilmenite operations.

This is 59 pct of the total ilmenite available from Australian primary-product ilmenite mines.

The United States has no primary-product ilmenite that can be recovered at a cost less than the January 1984 market price of $42/mt; the 24 million mt of ilmenite potentially recoverable from primary-product deposits in the United States are associated with costs well above the January 1984 market price of $42/mt.

As shown in table 11, the tonnage of ilmenite concentrates potentially recoverable from primary-product ilmenite mines that were in production in January 1984 is 147 million mt. This is 83 pct of the total primary-product ilmenite potentially recoverable. The amount potentially recoverable at a total cost of less than the January 1984 U.S. market price of $42/mt is 145 million mt, or almost 99 pct of the total.

A total in excess of 30 million mt is potentially recoverable from nonproducing primary-product ilmenite deposits. This is about 17 pct of the total potential recoverable ilmenite concentrates associated with primary ilmenite operations. Very little of this could be produced at a cost below $42/mt.

Ilmenite potentially recoverable as a byproduct from primary-product rutile mines was over 60 million mt in January 1984. This is about 24 pct of the total ilmenite recoverable from all sources. India and Sri Lanka have 28 million mt, 47 pct of the byproduct ilmenite potentially recoverable from primary-product rutile mines; Australia has 19 million mt, or 31 pct.

The total availability curve for byproduct ilmenite from primary-product rutile mines is illustrated in figure 17*B*. (The curve does not include a small quantity of ilmenite associated with costs greater than $1,200/mt of rutile.) Ilmenite tonnage is associated with the cost of rutile because only primary-product rutile operations are included here; therefore, the viability of each operation is determined by the viability of rutile production. About 37 million mt of byproduct ilmenite is potentially recoverable at a primary-product rutile cost less than the January 1984 rutile concentrate market price, which was $347/mt. This is about 62 pct of the total byproduct ilmenite potentially recoverable from primary-product rutile mines. Much of this byproduct ilmenite is presently being stockpiled. Revenues from the stockpiled ilmenite are not included in the analysis. A total of 11.6 million mt of ilmenite is considered as stockpiled material from a total of 10 mines and deposits, most of which are located in eastern Australia. Ten percent of this total is from mines presently producing.

More than 7 million mt of ilmenite are potentially recoverable as a coproduct from synthetic rutile operations; this is less than 3 pct of all ilmenite potentially available. Over 5 million mt are potentially recoverable at costs at or below the January 1984 market price for synthetic rutile, $350/mt.

Ilmenite resources used in the production of titanium slags, synthetic rutile, or as a mixed ilmenite-leucoxene-rutile product (as in Du Pont's operations in the United States) are discussed later in this section.

This study indicates that ilmenite resources are vast and that the majority of low-cost ilmenite is contained in European deposits. It also demonstrates that there is a significant amount of low-cost ilmenite that is not being produced or sold. This ilmenite is associated with primary-product rutile operations and was stockpiled rather than sold under the market conditions prevailing in January 1984. Much of this ilmenite has a high content of chrome, which is considered a deleterious material.

Leucoxene

It is estimated that approximately 2.9 million mt of leucoxene concentrate, containing approximately 67 pct TiO_2, is potentially recoverable as a byproduct of primary-product rutile, primary-product ilmenite, or the synthetic rutile operations included in this study (table 12). These resources comprise only a small portion of the titanium resources included in this analysis.

Leucoxene potentially recoverable from resources located in Australia is 2.4 million mt of concentrate, or 82 pct of the total. The remaining 500,000 mt are located in India and the United States. Producing mines in Australia account for 63 pct of the total for Australia, or 1.5 million mt.

Curves were not drawn for leucoxene because of the small number of deposits. Potentially recoverable leucoxene concentrate associated with six primary-product rutile mines included in the analysis is 1.4 million mt, which could be recovered at a cost of production for the associated rutile lower than its January 1984 market price.

Potentially recoverable leucoxene concentrate associated with five primary-product ilmenite mines included in the analysis is about 1.0 million mt; 82 pct of these concentrates could be recovered at a cost of production for the associated ilmenite lower than its January 1984 market price. Leucoxene concentrates associated with two synthetic rutile operations included in the analysis are 500,000 mt. All of these concentrates can be produced at a cost lower than the January 1984 synthetic rutile market price.

Table 12.—Total estimated recoverable leucoxene concentrates, as of January 1984

(Thousand metric tons of product)

	Australia	India	United States	Total
As a byproduct from primary-product rutile:				
Producers	260	342	122	724
Nonproducers	677	0	45	722
Total	937	342	167	1,446
As a byproduct from primary-product ilmenite:				
Producers	748	0	0	748
Nonproducers	215	0	0	215
Total	963	0	0	963
As a byproduct from synthetic rutile: Producers	490	0	0	490
Grand total	2,390	342	167	2,899

Synthetic Rutile

It is estimated that 15.5 million mt of synthetic rutile concentrate, containing approximately 93 pct TiO_2, is potentially available from five properties in which ilmenite is being used to feed synthetic rutile plants (table 13).

Table 13.—Total estimated recoverable synthetic rutile concentrates, as of January 1984

(Thousand metric tons of primary-product synthetic rutile)

	Australia, New Zealand	India	Total
Producers	2,341	11,054	13,395
Nonproducers	2,147	0	2,147
Total	4,488	11,054	15,542

Table 14.—Total estimated recoverable titanium slag, as of January 1984

(Thousand metric tons of primary-product slag)

	Australia	Brazil	Canada	Republic of South Africa	United States	Total
Producers	0	0	79,933	9,098	0	89,031
Nonproducers	5,092	13,710	5,837	0	2,542	27,181
Total	5,092	13,710	85,770	9,098	2,542	116,212

The synthetic rutile operations included in the analysis represent those with current or proposed production of synthetic rutile from ilmenite. The plants included are located in Australia and India, with the only nonproducer located in New Zealand. Synthetic rutile plants located in the United States, Japan, Malaysia, and Taiwan were not included because the source of the ilmenite processed could not be determined.

Much of the ilmenite potential, discussed in earlier sections of this report, could be processed to produce synthetic rutile if new plants were built. The world resources of ilmenite are very large, and the costs to produce ilmenite and convert it to synthetic rutile are quite comparable to those for the production of rutile; therefore, the potential production of synthetic rutile could be significant in the future. Owing to the fact that the long-run availability of rutile is limited, the production of synthetic rutile is expected to grow.

Titanium Slag

It is estimated that 116 million mt of titanium slag, containing at least 71 pct TiO_2, is potentially recoverable from the five properties included in this study (table 14). Slag potentially recoverable from two properties in Canada is 86 million mt, 74 pct of the total slag included in this study. Slag potentially recoverable from the Republic of South Africa is 9 million mt, almost 8 pct of the total slag included in this study. Producing operations, all of which have a cost of production below the market prices of $159/mt for Sorel slag and $181/mt for Richards Bay slag, have resources of 89 million mt potentially recoverable. This is 77 pct of the total titanium slag potentially recoverable from properties included in this study.

The quantity of titanium slag that potentially is recoverable, as with that of ilmenite, is large. Some slag is high grade and has been used in place of rutile as a feed for chloride pigment production. Additional high-grade slag may be potentially recoverable in the future. QIT, the producer of Sorel slag in Canada, has recently upgraded its slag to 80 pct TiO_2 (*25*).

Anatase

Anatase potentially recoverable from three nonproducing properties in Brazil is 38 million mt of concentrate. Although it has a slightly lower grade, anatase is a potential replacement for rutile. One of the Brazilian properties, Tapira, was being developed during 1984, with the other two in pilot plant stages. Since there is no published market price for anatase, cost comparisons are not possible. However, the total cost of production estimated for these deposits is between the present market prices of rutile and ilmenite.

Miscellaneous Titanium Operations

It is estimated that 6.8 million mt of a mixed ilmenite-leucoxene concentrate are potentially available from four properties in the southeastern United States (two producing and two nonproducing). This high-grade concentrate (greater than 60 pct TiO_2) is used or would be used for the specially designed Du Pont chloride plants. Du Pont owns the two producing properties. Since the product is produced and consumed in integrated operations, total cost comparisons are not possible.

A deposit in Colorado contains demonstrated resources of perovskite. Since there are no published prices, cost comparisons are also not possible.

A producing glass sand mine in the southeastern United States with demonstrated resources of ilmenite is included in the analysis. The ilmenite would be a byproduct, but it was not being produced during 1984.

ANNUAL AVAILABILITY

Annual availability curves are disaggregations of the total resource availability curves showing potential availability on an annual basis. Each curve represents a specific cost level. The horizontal axis represents time, either actual years for producers, or the number of years following the commencement of development for nonproducing operations. The vertical axis represents the annual production level.

Rutile

Figure 18 shows the projected annual capacities for rutile mines that were in production at the time of this analysis. The curve, representing annual production at operations with costs of production less than the January

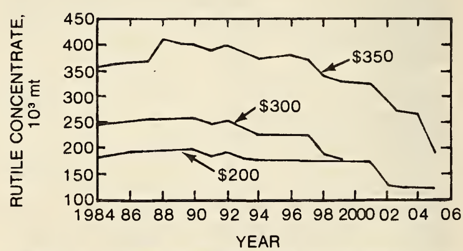

Figure 18.—Annual availability curves for producing rutile mines, at various total costs of production.

1984 market price of approximately $350/mt, gradually declines until the year 2000 and then decreases dramatically. The curve shows that in 1984 about 350,000 mt could be produced at a cost less than $350/mt. Australian production is 48 pct of this, or 170,000 mt. These figures compare closely with the world rutile production for 1981 of just over 350,000 mt (minus the U.S.S.R.) and 230,000 mt for Australia (see table 1). This curve illustrates that by the year 2000 a projected annual amount of about 320,000 mt could be produced for a cost of production equal to or less than $350/mt. This is 91 pct of 1984 production, representing only a slight decline at this point. Australia could produce 46 pct of this, or 147,000 mt. Shortly after the year 2000, production of rutile concentrates from mines producing as of January 1984 is likely to decline significantly as the demonstrated resources from many mines, particularly in Australia, are depleted. This decline could be offset if new resources are found, if inferred tonnages become demonstrated, or if production begins from properties that currently are not producing, such as the higher cost rutile mines or the Brazilian anatase deposits.

Annual availability curves showing the projected annual production for deposits that were not in production at the time of this analysis are shown in figure 19. As illustrated, the cost of production from these properties is significantly greater than the current market price of rutile concentrates. The price of rutile would have to increase significantly in order for most of these operations to generate the revenues necessary to cover their high costs. This also illustrates, on an annual basis, the point made in the discussion of the total availability of rutile, that most of the economical rutile resources are currently in production.

The three curves in figure 19 represent annual production at operations with costs less than $450/mt, $600/mt, and $900/mt. All three curves reach their highest production level 4 yr after initiation of development, assuming all of these properties were to initiate development in the same base year. At this peak year, the $450/mt curve shows a potential production level of 80,000 mt/yr, all from Australia; the $600/mt curve reaches 182,000 mt/yr, 63 pct from Australia; and the $900/mt curve reaches a production level of 310,000 mt/yr, 71 pct from Australia.

All three curves show a decline in production over a period of 16 yr. At this point there is no production at the $450/mt cost level, and the $600/mt curve shows a potential production of 103,000 mt/yr, 34 pct from Australia. The $900/mt curve shows a potential production of 182,000 mt/yr, 52 pct from Australia. The rutile available from the

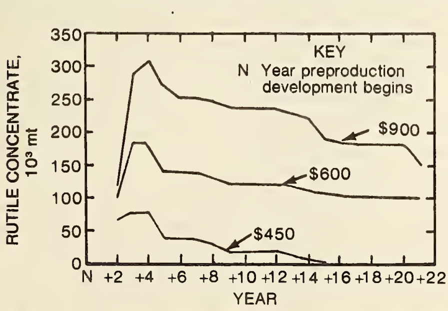

Figure 19.—Annual availability curves for nonproducing rutile mines, at various total costs of production.

nonproducing mines in this analysis could replace the rutile from producing mines when they become depleted, but at substantially higher costs. The higher costs also should encourage the development of alternate sources, including synthetic rutile production from ilmenite concentrates. Rutile from the nonproducing deposits not only is high in cost, but is very limited in quantity; therefore, it could act as a replacement only for a limited amount of time, given a static resource base and production at full-capacity levels.

Ilmenite

Annual production from producing operations of both primary-product and byproduct ilmenite, with costs near or below market prices, could potentially have been 2.7 million mt/yr in 1984. This quantity may not match actual production figures because it assumes mines are operating at full capacity and includes byproduct ilmenite, some of which is assumed in this analysis to be stockpiled and not sold. In addition, most published data for ilmenite production include ilmenite going to slag or synthetic rutile, while the present analysis treats this ilmenite separately.

Annual production of both primary-product and byproduct ilmenite from nonproducing deposits could potentially be a maximum of 2.4 million mt/yr. Those nonproducing operations with costs of production equal to or less than twice the January 1984 market prices could produce annually a maximum of 1.1 million mt. There is very little potential annual production of ilmenite from nonproducing deposits with costs of production near or below the January 1984 market price.

Leucoxene

Annual availability of leucoxene concentrate with costs near or below the market price could potentially have been 73,200 mt in 1984; this includes leucoxene as a byproduct of producing primary-product rutile operations and primary-product ilmenite operations, or from mines feeding synthetic rutile operations.

Annual availability of leucoxene from nonproducing rutile and ilmenite deposits could potentially be 76,200 mt/yr. At a cost of production less than the January 1984 market prices, annual production from nonproducing operations could be 65,200 mt.

Synthetic Rutile

Annual availability of synthetic rutile from the producing operations included in this study potentially have been a maximum of 193,300 mt in 1984. The one nonproducing synthetic rutile operation (Barrytown in New Zealand) could not cover its costs at the January 1984 market price.

Titanium Slag

Annual availability of titanium slag from producing operations could potentially have been a maximum of 1.2 million mt in 1984. This compares closely with the 1981 world production value of 1.1 million mt of slag. At that level, slag production could be maintained into the next century. Annual availability from nonproducing slag operations (one each in the United States, Brazil, and Australia) could potentially be more than 800,000 mt/yr. No nonproducing slag operations could cover their costs at the January 1984 market price.

Table 15.—Total potentially recoverable zircon concentrates, as of January 1984

(Thousand metric tons of product)

	Australia, New Zealand	Brazil	India, Sri Lanka	Republic of South Africa	United States	Total
As a byproduct from primary-product rutile:						
Producers	4,312	0	1,817	0	302	6,431
Nonproducers	4,393	0	0	0	1,278	5,671
Total	8,705	0	1,817	0	1,580	12,102
As a byproduct from primary-product ilmenite:						
Producers	1,018	302	0	0	0	1,320
Nonproducers	1,294	0	0	0	77	1,371
Total	2,312	302	0	0	77	2,691
As a byproduct from other titanium sources:[1]						
Producers	2,977	0	231	3,022	1,150	7,380
Nonproducers	163	0	0	0	817	980
Total	3,140	0	231	3,022	1,967	8,360
Grand total	14,157	302	2,048	3,022	3,624	23,153

[1]Includes slag operations, mines and deposits producing a mixed titanium product, and those ilmenite mines feeding synthetic rutile plants.

Anatase

No anatase mines were operating as of January 1984, although development continued. Annual availability of anatase from nonproducing operations could potentially be a maximum of 281,000 mt/yr. This large annual tonnage of anatase is a significant potential replacement source for rutile and could be maintained for approximately 20 yr.

Mixed Concentrate

Annual availability of a mixed concentrate of ilmenite and leucoxene from both producing and nonproducing operations could potentially be a maximum of 243,800 mt/yr.

AVAILABILITY OF BYPRODUCT ZIRCON

In addition to the various titanium minerals recoverable from beach sand operations, zircon concentrates often contribute significantly to the economic viability of an operation. It is estimated that zircon concentrates that could be recovered from 41 mines and deposits included in this study total just over 23 million mt. The zircon concentrates, which contain approximately 65 pct ZrO_2, are a byproduct of the titanium operations. Potential zircon concentrates recoverable from resources located in Australia account for nearly two-thirds of the total, while those in the United States account for only 16 pct.

Table 15 shows that 65 pct of all recoverable zircon concentrates included in this study would come from mines that were producing titanium concentrates as of January 1984. This quantity represents the amount of zircon concentrates available at roughly the market prices for the various titanium products. The largest portion of this is from producing mines in Australia (55 pct).

The revenues generated from the production of zircon concentrates can often be quite significant. Table 16 shows that as much as one-third of the revenues generated from many of the operations in this study are from zircon concentrates, based on January 1984 market prices for all commodities recovered. The ratio between revenues generated by titanium concentrates (rutile and ilmenite) and those generated by zircon concentrates ranges from a low of 66 to 33 to a high of 82 to 9. Although titanium concentrates are clearly the primary or most significant product produced from most of the mines included in this study, zircon concentrates can be a very significant revenue generator, even to the extent of making the difference as to whether the mine is economically viable.

Table 16.—Average revenue distribution for selected mines producing zircon, based on 1984 market prices

(Percent)

	Australia		India, Sri Lanka	United States
	East coast	West coast		
From rutile	75	9	44	W
From ilmenite	1	65	38	W
Total	76	74	82	66
From zircon	23	7	9	33
From other commodities	1	19	9	1

W Withheld to avoid disclosing company proprietary data.

It is interesting to note that one of the regions of the world that produces large quantities of rutile (the east coast of Australia) also produces significant amounts of zircon. This relationship can be seen in the form of revenues generated. The west coast of Australia, where ilmenite is most often the primary commodity from the beach sand operations, produces significantly less zircon and this too is reflected in terms of the revenues generated.

The availability of zircon concentrates on an annual basis was also considered. At the January 1984 market price for titanium concentrates, over 570,000 mt of zircon was available in 1984 from the producing mines included in this study. This compares quite well with the nearly 550,000 mt produced in 1981 (excluding the U.S.S.R. and China) (*26*, p. 934). Owing to the fact that a majority of zircon is produced from rutile mines, which this study shows will be depleting after the turn of the century, the annual availability of zircon concentrates from producing mines should also be on the decline. An additional 350,000 mt/yr of byproduct zircon, at the minimum, could be available in the future from deposits presently not in production, but at costs substantially higher than the January 1984 market prices for the various titanium products.

The availability of hafnium can be directly related to the availability of zircon, since they are nearly always found together in nature. As a rule-of-thumb, there is typically 2 pct hafnium found with zirconium (or HfO_2 equal to 2 pct of the amount of ZrO_2). Therefore, based on the quantity of zircon concentrates this study has shown to be available (over 23 million mt) as of January 1984, a total of 463,000 mt HfO_2 is also available.

CONCLUSIONS

Titanium is used primarily in the form of TiO_2 as a source of pigments. Titanium metal is considered a strategic and critical material for the United States because of its defense and aerospace applications. In an attempt to assess the worldwide availability of titanium mineral resources, the Bureau evaluated 63 mines and deposits in market economy countries. The selected mines and deposits include all known resources of titanium at the demonstrated resource level that met the criteria of the study and that can be mined and processed with current technology, as of January 1984.

Approximately 438 million mt of TiO_2 is contained in the demonstrated resources of these mines and deposits. These resources include 115 million mt in North America (the United States and Canada), 93 million mt in South America (Brazil), 120 million mt in Europe (Finland, Italy, and Norway), 40 million mt in Asia (India and Sri Lanka), 20 million mt in Africa (Sierra Leone and the Republic of South Africa), and 50 million mt in Oceania (Australia and New Zealand). In addition, the studied deposits also contain approximately 314 million mt of contained TiO_2 at the inferred resource level.

Approximately 29 million mt of rutile concentrate is potentially recoverable from 40 deposits analyzed, 39 pct from producing mines. Approximately 11 million mt of rutile is potentially recoverable at total production costs of less than the January 1984 market price of $347/mt. About 25 million mt could be available at a net production cost of twice the January 1984 market price. Australia accounts for about one-third of the total rutile concentrate available.

In terms of annual availability, it is estimated that approximately 350,000 mt/yr of rutile concentrate was available in 1984, from mines producing at the time of this study, at a cost of production less than the January 1984 market price. This compares with actual 1981 production, excluding the U.S.S.R. The analysis showed that after the year 2000, production of rutile concentrates from producing mines will decline significantly as many mines, particularly in Australia, deplete their currently estimated demonstrated resources. This would indicate that within the coming decade there could be a shortage of high-grade, low-cost rutile. Potential production from the nonproducing rutile deposits could act as a replacement source for a limited amount of time, but at a substantially higher total cost. Production could continue from the present producers if new resources were discovered at their deposits or if any of their inferred tonnage were to become demonstrated, although this would seem less likely.

Approximately 246 million mt of ilmenite concentrate is estimated to have been recoverable, as the primary product (72 pct of the total) or as a coproduct or byproduct of rutile, from the deposits included in this study. Over 187 million mt of this is potentially available at a total cost of less than the January 1984 market prices (145 million mt from primary-product ilmenite, 37 million mt as byproduct from rutile, and 5 million mt as byproduct with ilmenite feeding synthetic rutile plants). European countries had by far the greatest portion (143 million mt) of all ilmenite resources, both primary and byproduct. These data indicate that an abundance of ilmenite is available, compared with other sources of titanium, paticularly rutile, although much of this ilmenite may not presently be usable because of high levels of chromium.

Annual production from producing mines of both primary and byproduct ilmenite in 1984 could potentially have been a maximum of 2.7 million mt/yr. An additional 1.1 million mt/yr is available from the nonproducing deposits at twice the January 1984 market prices.

Much of the ilmenite potential discussed in this report could be used to produce synthetic rutile if new plants were built. The world resources for ilmenite are very large, and the costs to produce ilmenite and convert it to synthetic rutile are quite comparable to those for the production of rutile; therefore, the potential production of synthetic rutile could be significant in the future. Owing to the fact that the long-run availability of rutile is limited, the production of synthetic rutile is expected to grow.

Demonstrated resources of leucoxene concentrates that are potentially recoverable as a byproduct of primary-product ilmenite and primary-product rutile mines are about 2.9 million mt. An additional 15.5 million mt of synthetic rutile concentrate is available from the synthetic rutile operations included in this study, and 116.2 million mt of titanium slag is also available. Anatase deposits in Brazil, a number of which are presently developing, include an additional 38 million mt.

This analysis has determined that in the long run, resources of rutile are limited. It has also determined that there are various other sources of high-grade titanium. Anatase deposits in Brazil have the potential to be a significant source; slag deposits in Canada and the Republic of South Africa could increase capacity; higher cost rutile deposits could be developed; and most importantly, an increased world synthetic rutile capacity, based on the large resources of ilmenite, could become the most significant resource, in the future, of high-grade titanium concentrate.

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APPENDIX A.—WORLD TITANIUM DEPOSIT GEOLOGY AND RESOURCES

The following discussions give an overview of the world resources of titanium by region. Included in these discussions are primarily those deposits evaluated for this study.

NORTH AMERICA

United States

Major titanium mines and deposits in the United States that were included in this study are shown on figure A-1. The figure shows the abundance of deposits along the east coast, most of which are beach-sand-type deposits.

The most important titanium resources of the United States, from a commercial standpoint, are located in Florida, just south of Jacksonville. There are three producing mines in this region, one owned by Associated Minerals Ltd., the Green Cove Springs Mine, and two owned by Du Pont, the Trail Ridge and Highland operations. These mines are believed to be ancient elevated beach sand deposits of Pliocene to Pleistocene age, although recent work has supported the statement that much of the Trail Ridge ore is aeolian dune (*27*, p. 30).[1]

[1]Italicized numbers in parentheses refer to items in the list of references preceding this appendix.

The Green Cove Springs ore body, located on the Duval Upland, is approximately 19 km long, 1 km wide, and 6 m thick, with the ore overlain by approximately 0.5 m of topsoil. The two Du Pont operations are actually one single ore body found on the Trail Ridge feature, separated by State Highway 225. The ore body on the Trail Ridge feature is approximately 27 km long, 4 km wide, and from 8 to 21 m thick. Here, too, the ore is located just below the thin topsoil.

Resources are estimated to be greater than 400 million mt of sand (or approximately 5 million mt of contained TiO_2) at the demonstrated level for both these deposits, and possibly as much as a billion tons of sand (over 10 million mt of contained TiO_2) when inferred resources are included (*2*). The average heavy-mineral content of these deposits is 3 to 4 pct. The most significant heavy minerals produced are rutile, altered ilmenite, leucoxene, zircon, and monazite. High-grade TiO_2 minerals account for about 45 pct of the heavy minerals at Trail Ridge (*28*). The Trail Ridge and Highland operations have been producing since 1949 and 1955, respectively, while the Green Cove Springs Mine started up in 1972.

Humphreys Mining Co. had been mining heavy minerals in Florida near the town of Boulougne during the 1970's, but by 1980, the deposit was completely mined out and, therefore, this mine was not included in our evaluation.

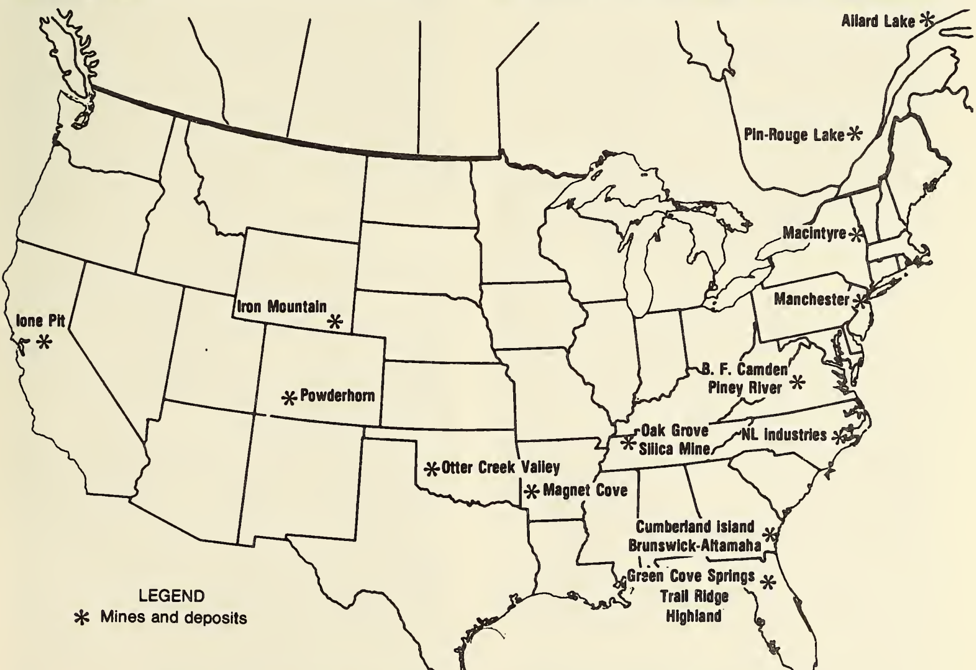

Figure A-1.—Location of titanium mines and titanium-bearing deposits of North America.

Two significant deposits in Georgia containing heavy minerals, particularly titanium, were included in the evaluation. Both are located in the southeast corner of the State, the Cumberland Island deposit on the coast just north of the Florida State line, and the Brunswick-Altamaha deposit slightly inland just north of the town of Brunswick. Neither of these deposits has ever been developed, although various drilling programs have defined the ore bodies. These deposits are placer beach sand deposits of Pleistocene to Recent age. The Cumberland Island deposit is located in the Silver Bluff Shoreline Complex covering the entire island (2,833 ha) and is overlain by 0.2 m of overburden. Heavy minerals are located in the upper, sandy unit. The Brunswick-Altamaha deposit is found in the Princess Anne Shoreline Complex. It is 10,460 m long and 805 m wide, and has a thickness of 4.6 m. It, too, is overlain by 0.2 m of topsoil.

Ilmenite is the major titanium-bearing ore mineral at both the Georgian deposits. Small amounts of rutile and/or leucoxene are present. Zircon and monazite may also be recoverable. The average heavy-mineral content of the Silver Bluff Shoreline Complex (for Cumberland Island) has been reported to be 1.7 pct, containing over 45 pct ilmenite, nearly 3 pct leucoxene, and almost 7 pct rutile. Zircon and monazite have also been reported to be nearly 13 pct and over 1 pct, respectively, of the heavy minerals (*29*). Demonstrated resources for the two deposits range from 200 to 500 million mt of sand (or from 1.5 to 4 million mt of contained TiO_2). Identified resources from old beach sands in Georgia have been reported to contain nearly 3 million mt TiO_2 (*2*).

The Brunswick-Altamaha deposit is presently owned by Union Camp Corp. (40 pct), the Jones family (40 pct), and the Brunswick Pulp and Paper Co. (20 pct), which did the drilling of the deposit in 1960. The Cumberland Island deposit is primarily owned by the U.S. Department of the Interior's National Park Service (86 pct). The remaining 14 pct is privately owned. The deposit was drilled out in the 1950's, and very little has been done since then.

The Folkston deposit, not included in the present study, was a significant producing titanium mine in Georgia (near the Florida border along the coast) throughout the 1960's and into the 1970's. Humphreys Mining Co. ceased operations there in 1974 because of the exhaustion of reserves.

The only deposit in North Carolina evaluated for this study is NL Industries' property located near the east coast of the State, west of the town of Aurora. The deposit consists of heavy-mineral sands occurring primarily in unconsolidated placer beach sands of Pleistocene to Recent age. The sand occurs in narrow strips within a zone 19 km long and 0.85 km wide. The average thickness of the ore zone is 6 m, covered by approximately 1 m of overburden. Although the heavy-mineral sands in this deposit are unweathered, poorly sorted, and contain various impurities (making processing and recovery more difficult), scattered pockets may contain as much as 15 pct heavy minerals. The average heavy-mineral content is 3 pct. Ilmenite is the primary titanium mineral present. Small amounts of zircon and rutile, although insufficient to recover, are also present. Reserves at this deposit have been reported to be 35 million mt of beach sand, or approximately 400,000 mt of contained TiO_2 (*30*). Various drilling programs defined this deposit in the 1950's, 1960's, and 1970's. This deposit has never been developed.

Two deposits in Virginia were included in the evaluation, both associated with ferrodiorites of the Roseland District. These deposits, the B. F. Camden Anomaly and the Piney River deposit, are located in Amherst County in the center of the State. Ilmenite is the major ore mineral at these deposits and is found either at the base of ferrodiorite sheets or with apatite in dikelike masses also known as nelsonite (*31*). The nelsonite deposits are higher grade but limited in size. Some rutile also exists in the district but is not significant in the two deposits studied. The B. F. Camden Anomaly ore body is just over 2 km in length and approximately 200 m wide. The ore zone averages 20 m thick under approximately 1 m of overburden. At the Piney River deposit, the ore body is nearly 900 m long, extending to a depth of over 120 m. Ilmenite grades average nearly 20 pct (10 pct TiO_2) at both these deposits, with demonstrated resources ranging from 20 to 30 million mt of ore (or 1 to 3 million mt contained TiO_2).

Ilmenite has been mined in New Jersey since the early 1960s. Glidden Industries operated the Lakehurst operation until it was closed in 1973; and the Manchester Mine, which is included in this evaluation, was operated by Asarco from 1973 until it was closed in 1981 for economic reasons. Even though this operation is presently closed and Asarco has no intention of ever returning (all equipment and structures are being dismantled and sold), it was included in this evaluation since some resources remain. It was evaluated from the standpoint of a nonproducing deposit that would need complete development to start production. Asarco retained the mineral rights to the deposit.

The Manchester deposit is located in northern Ocean County, NJ, southwest of the town of Lakehurst. The ore is found in the Cohansey Sand formation, of late Miocene or Pliocene age. The formation is a medium-grained poorly sorted quartz sandstone approximately 30 m thick. It lies unconformably on the Kirkwood Formation of Miocene age. The Cohansey, in the central part of the State, is ilmenite rich and has been the only formation mined, although heavy minerals are present above and below it. Resources for the Manchester Mine were originally estimated to be on the order of 163 million mt at 1.95 pct TiO_2 (*32*). Once production through January 1981 is subtracted (approximate time of shutdown), approximately 100 million mt of ore (2 million mt contained TiO_2) remain.

The entire district, including both the Manchester deposit and the old Lakehurst Mine, had been estimated by Markewiez in 1969 to contain as much 11.3 million mt of contained TiO_2 resources (*33*). Subtracting production to date, the district may contain as much as 10 million mt of contained TiO_2 (*2*). These estimated resources should probably be considered identified since they may include both demonstrated and inferred resources. The heavy-mineral content at these deposits ranges from 3 to 15 pct, averaging 4 to 5 pct (*28*). Altered ilmenite makes up 85 to 90 pct of the heavy minerals (*33*).

The only deposit in New York included in this evaluation is the MacIntyre Development, located near Tahawus, in Essex County. The MacIntyre Development is within the Precambrian Sanford Lake magnetite district in the midst of the Adirondack Mountains. Although titaniferous magnetite deposits have been known to exist in the Adirondacks since the 1800's, no significant development occurred until National Lead Co. (now NL Industries) began developing the Sanford Hill ore body in the early 1940's. Iron (from magnetite) and titanium (from ilmenite) have been produced from this region since then, moving to the south (the South Extension) in the 1960's. As of the end of 1982, the ilmenite concentrates have been stockpiled, since NL's pigment plant in Sayreville, NJ, the main

consumer of MacIntyre's ilmenite, has closed because of economic conditions.

Anorthositic ore, occurring as massive lenses, and gabbroic ore, occurring as oxide-enriched bands, are both found at the South extension, where mining presently exists. The Sanford Lake district contains four major ore bodies: the Sanford Hill-South Extension, the upper works (also called Calamity-Mill Pond), Mt. Adams, and Cheney Pond, where mining activities would probably occur next. Demonstrated resources, used in this evaluation, include the Sanford Hill-South Extension (nearly mined out) and Cheney Pond. It has been reported that total resources for the entire district are 8.6 million mt of contained TiO_2 (*2*). The TiO_2 grade ranges from 10 to 30 pct (*28*) throughout the district although it is closer to 15 to 20 pct at the South Extension and Cheney Pond. Small amounts of vanadium (0.5 pct V_2O_5) exist in the magnetite phase throughout the district but are not recovered. Iron grades range from 15 to 30 pct at the South Extension and Cheney Pond.

Two deposits in Tennessee were included in the evaluation, the Oak Grove deposit and the Silica Mine. Both deposits occur in the Cretaceous McNairy Sand formation at the eastern edge of the Mississippi River Embayment. The deposits, located in northwestern Tennessee, are secondary, ancient marine beach sands. The Silica Mine presently produces only a quartz sand product. Altered ilmenite and rutile are the major heavy minerals at both deposits, with zircon, leucoxene, staurolite, kyanite, tourmaline, and monazite also potentially recoverable. Resources for this region have not been published for specific deposits but are estimated by the U.S. Geological Survey and the Bureau of Mines to be 8.4 million mt contained TiO_2 from the ilmenite and 1.3 million mt contained TiO_2 from the rutile (*2*). This estimated resource is at the identified level and contains more tonnage than at Oak Grove and the Silica Mine. These estimates seem to include tonnage owned by Kerr-McGee and in Natchez Trace, which was not included in this evaluation because of a lack of information.

Oak Grove is owned by the Ethyl Corp. and is located in Henry County. The ore body is over 20 km long and 8 km wide, and approximately 12 m thick with 12 m of overburden. Although the deposit was explored in the early 1970's, no development has ever occurred.

Silica sand is produced by the Tennessee Silica Sand Co. (a subsidiary of Jesse S. Morie and Sons, Inc.) at the Silica Mine in Benton County. This deposit, about 400 ha in extent, and with sand outcropping in many places, has a minable ore thickness of about 4 m. The mine has been in production for more than 40 yr and has only recently been acquired by its present owners.

There are three known significant titanium deposits in Hot Spring County, AR; only the Magnet Cove deposit, just north of the city of Hot Springs, was included in this analysis. The other two, both of which have never produced, are the Christy deposit and the Hardy-Walsh deposit. The Magnet Cove deposit produced about 5,000 mt of rutile concentrate from 1932 to 1944. The Magnet Cove deposit has been owned by various companies and is now held in fee by numerous private owners.

These deposits in northern Hot Springs County are part of a complex mixture of alkalic igneous rocks (the throat of an ancient volcano), Cretaceous in age, intruding into folded sedimentary and metamorphic rocks (*28*). Rutile and brookite are the most significant titanium minerals present.

In situ resources of ore remaining at the Magnet Cove deposit have been reported to be just over 7 million mt at 2.6 pct TiO_2 (or nearly 200,000 mt of contained TiO_2) (*34*). Small amounts of columbium are also present but not in quantities sufficient for recovery. Idealized dimensions of this ore body are 580 m in length and 151 m in width. Maximum pit depth is presently 9 m, with little or no overburden, and the ore body has been drilled to depths of at least 41 m. The Christy deposit was drilled by the Bureau in 1948 and, although no quantification of resources was made, it has been stated that the ore body contains 5.8 pct TiO_2 (*35*).

An alluvial river sand deposit of Quaternary age in southwestern Oklahoma (Kiowa and Tillman Counties) was included in this evaluation. The Otter Creek Valley deposit, located along the southwest flank of the Wichita Mountains, 3.5 km west of the town of Snyder, is a portion of the valley fill within the Otter Creek drainage system. These ilmenite-bearing black sands, first recognized by the Oklahoma Geological Survey in the early 1950's, were extensively investigated by the Bureau in the late 1950's. There has never been any development at this deposit and no further studies since the Bureau's 1960 report (*36*).

The Otter Creek Valley deposit is approximately 20 km long and 2 km wide. The thickness of the deposit averages 7.6 m (a basal sand-clay component), while the overburden averages 5.9 m thick (a silt-clay alluvium).

The indicated potential resource for the Otter Creek Valley deposit was estimated to be approximately 340 million mt of alluvial material containing 1.24 pct TiO_2 (or 4.2 million mt of contained TiO_2) (*36*). The TiO_2 is in the form of ilmenite. Small amounts of columbian are also present but not in sufficient quantities for recovery. The resource estimated by the Bureau in 1960 includes the northern portion of the deposit, flooded by a reservoir. It is estimated that of the 340 million mt, only 317 million mt with a grade of 1.23 pct TiO_2 (or 3.9 million mt of contained TiO_2) would be available for mining. The deposit has no clear overall owner, since it is covered by a collection of numerous individual landholders who may or may not own the mineral rights.

The Powerhorn titanium deposit, owned by Buttes Gas and Oil Co., was the only deposit in Colorado evaluated for this study. It is located 40 km southwest of the town of Gunnison, in the southwestern part of the State of Colorado. The deposit is an alkalic igneous stock and carbonatite, which intruded a Precambrian host rock, consisting of granites and other metamorphic rocks, approximately 550 million yr ago (Cambrian period). The carbonatite is surrounded by pyroxenite, which, primarily in northeastern half of the complex, contains the titanium-bearing mineral perovskite, together with magnetite. The perovskite and magnetite occur as both irregular lenslike bodies several feet long and an accessory minerals in the pyroxenite. The ore body has been studied and drilled out at various times from the 1950's to the late 1970's. Holes drilled to a depth of 180 m had not determined the lower limits of mineralization. The deposit is 4 km long and 0.6 km wide.

Resources for the Powderhorn deposit were published in a 1976 Wall Street Journal article as 380 million mt averaging 12 pct TiO_2. This was classified as 88 million mt measured, 158 million mt indicated, and 134 million mt inferred (*37*). Although the ore body is reported to be 12 pct TiO_2 in total, much of this titanium is mineralogically "locked up" in augite, magnetite, mica, and even leucoxene. The major recoverable titanium mineral, perovskite, contains the only potentially recoverable TiO_2 from the ore body. It has been estimated that recoverable perovskite is approximately 8 pct of the ore body and that the perovskite contains only about 50 pct TiO_2. Therefore, only 4 pct TiO_2 would be realized, resulting in 9.8 million mt contained TiO_2 at the demonstrated level and an additional 5.9 million mt

contained TiO_2 at the inferred level. Columbium and rare earths are also present in this deposit; the rare earths are considered to be of commercial significance. Little has been done with this deposit since Butte's drilling program in 1976.

The Iron Mountain titaniferous magnetite deposits, located in the Laramie Range, were included in this evaluation. The deposits are in southeastern Wyoming, approximately 76 km northeast of Laramie. The rocks in this region are predominantly a metamorphic Precambrian complex intruded by anorthosites and associated igneous rocks, which were subsequently intruded by dikes of granite and magnetite-ilmenite (*28*). The main Iron Mountain dike contains the major ore deposits occurring as either massive megnetite-ilmenite or as disseminated magnetite-ilmenite. In either case, ore is composed of extremely fine intergrowths of magnetite and ilmenite and occurs as irregular masses or as streaks in the central areas of the anorthosite. Since most of the ilmenite is combined with the magnetite, these intergrowths would have to be upgraded using a smelting process similar to that used by QIT in Sorel.

Resources for the high-grade massive ore at Iron Mountain have been estimated to be 30 million mt with an average grade of 45 pct Fe and 20 pct TiO_2. The lower grade disseminated ore has been estimated to be 148 million mt with an average grade of 20 pct Fe and 9 pct TiO_2. Much of this material was classified as inferred. The resource value used for this evaluation was a portion of the high-grade massive ore (*38*).

The Iron Mountain deposits were drilled and evaluated in the 1950's and 1960's. They are owned by Rocky Mountain Energy Co., a subsidiary of Union Pacific (64 pct), and by Anaconda, a subsidiary of ARCO (35 pct). The remaining 1 pct is controlled by local ranchers. The deposit has never been developed.

The evaluation also included a clay-producing operation in central California near the town of Ione. The waste material found in the tailings pond from this mine (called the Ione pit and mill) contains titanium, in the form of altered ilmenite, and zircon. The commercially important clay, sand, and lignite deposits of this region are found in the Tertiary Ione Formation. The waste material, which could be reprocessed for the heavy minerals, contains just over 1 pct zircon (ZrO_2) and 20 pct ilmenite (10 pct TiO_2) (*39*). No published resources exist. The mine is owned by North American Refractories Co. and has been operating since 1954.

Additional United States Resources

The following section briefly describes those U.S. deposits not included in this evaluation. Most of these were too small to include, or their resource is not presently extractable with today's technology, or the resource was not at the demonstrated level. Unless otherwise noted, the resource level was not stated in the literature. Most of the resource values that were given in the literature are probably inferred estimates.

Florida phosphate deposits contain various heavy minerals, including rutile, ilmenite, zircon, and monazite, found in the Pliocene Bone Valley Formation (*40*). The Bureau has studied the potential for recovering these heavy minerals from the flotation circuits of central Florida phosphate mines. Although commercial-grade concentrates were produced, the heavy-mineral recoveries were extremely low owing principally to the fineness of grain size (*41*). Resources have been estimated to be at least 200,000 mt TiO_2 (*2*).

The Bureau has also investigated the potential for recovering heavy minerals from sand and gravel operations in Alabama. The most significant heavy minerals found in these Cretaceous sand operations were ilmenite (an altered form), rutile, zircon, kyanite, and monazite. The study found that the occurrence of heavy minerals in these operations is widespread (*42*). Other Bureau studies have investigated the potential recovery of rutile as well as various heavy minerals from sand and gravel operations throughout the southeastern United States (particularly Alabama, Georgia, North Carolina, and South Carolina) (*43-44*). The resource could be substantial based on the number of sand and gravel operations in that region and, in fact, has been estimated to be as much as 400,000 mt of contained TiO_2 from Alabama and Georgia operations (*2*).

The Bureau has also investigated the potential to recover byproduct heavy minerals from sand and gravel operations in Oregon and Washington (*45*) and in central and southern California (*46*). Resources in these regions were not estimated, with the exception of Ione.

Various old beach sand deposits have been investigated in South Carolina. One source estimates identified resources of 3.8 million mt of ilmenite and 1.0 million mt of rutile (together equaling approximately 3.0 million mt of contained TiO_2) from 11 of these deposits (*47*, p. 7). The Charleston area deposits contain an additional resource, containing 2 million mt of heavy minerals (*48*, p. 14).

The Natchez Trace area of Tennessee, in Henderson County, is reported to have over 7 million mt of heavy minerals containing significant quantities of rutile (250,000 mt) and ilmenite (4.1 million mt) as well as various other heavy minerals (*49*, p. 17; *50*, p. 24). There could be as much as 2.5 million mt of contained TiO_2.

Ilmenite resources on the western side of Ship Island, MS, have been reported to be on the order of 200,000 mt (100,000 mt contained TiO_2) (*51*, p. 23). Ship Island is a modern barrier island in the Gulf of Mexico.

An ilmenite mine in Caldwell County, NC, called the Yadkin Valley deposit, produced high-grade ilmenite from 1942 to 1952. The deposit consists of small masses of ilmenite in a quartzite and mica schist. The TiO_2 grade (49 to 52 pct) has been considered unusually high for a rock-type ilmenite (*28*). Remaining resources have been estimated to be 200,000 mt of contained TiO_2 (*2*).

The Willis Mountain Mine, a producing kyanite mine in Virginia, is reported to have 300,000 mt of contained TiO_2 resources. This value is based on the rutile content of identified kyanite resources (*2*).

In the serpentinite belt of Harford County, MD, rutile is found in significant quantities in the ultramafic chlorite rock. Although averaging approximately 1 pct rutile, some pockets contain as much as 16 pct (*52*). Resources for this deposit have been estimated to be 700,000 mt of contained TiO_2 at the identified level (*2*).

The Port Leyden heavy-mineral deposit, at the edge of the Adirondack Mountains in New York, contains significant quantities of low-grade ilmenite and zircon resources. The ilmenite sands are found in Pleistocene glacial deposits. Although the grade of the TiO_2 in the ilmenite is only 25 pct, there is a reported 31 million mt of ilmenite at this deposit (7.8 million mt of contained TiO_2). Inferred resources have been estimated to be on the order of 2.4 billion mt of sand with an ilmenite grade of 1.5 pct. Zircon and small quantities of rutile also are present at this deposit (*53*). Technology to recover this ilmenite resource is questionable, and therefore, this large resource has never been considered for development. Resources discusssed here are only for the

Port Leyden Quadrangle. Possibly more tonnage exists outside that area.

The Duluth Gabbro Complex of mafic igneous rocks in Minnesota has recently been studied to determine various byproduct recoveries. Of interest is the large quantity of ilmenite that could potentially be recovered. It was estimated that over 500,000 mt/yr ilmenite with a grade of 50 pct TiO_2 could become available from the copper-nickel tailings (*54*). Resources for the complex, at the identified level, have been estimated at 10 million mt of contained TiO_2 (*2*).

Various rare earths were mined from Idaho alluvial placer deposits in the 1950's. Ilmenite does exist at these deposits and could be recovered, although the grade is very low. These resources would become significant only if mining for rare earths ever reoccurred.

Some years ago, the Bureau studied the titaniferous Cretaceous shoreline sandstones of Utah, Wyoming, New Mexico, and Colorado. In that reconnaissance, nearly 28 million mt of sandstone containing an average of 7 pct TiO_2, equivalent to 2 million mt contained TiO_2, was quantified (*55*, p. 8). The titanium minerals present were ilmenite and altered ilmenite. Some zircon and monazite were also found to be present in these deposits. The resource estimate was based on field sampling and dimensional calculations, and therefore the resource level should not be considered any greater than inferred. Technology to recover these resources is unproven.

A rutile deposit was discovered in 1968 in a Precambrian gneiss near Evergreen, CO. Average rutile grade was 2.1 pct in an indicated resource estimated to be 115,000 mt of rutile, with additional inferred resources of 47,000 mt rutile for every 30 m in depth below the 73 m measured. Although this resource was determined to be recoverable, it was felt that it would never be mined owing to both environmental and economic factors (*56*).

Deposits similar to the type found in Evergreen, CO, are also found in Farmville District, VA, Kings Mountain District, NC and SC, Graves Mountain, GA, White Mountain, CA, Yuma County, AZ, and Santa Cruz County, AZ (*56*).

Preliminary studies have been made by both the U. S. Geology Survey and the Bureau to determine the potential for recovering rutile from porphyry coper tailings in Arizona and Utah. The Geological Survey work has estimated that 8 million mt of recoverable rutile may exist at just three deposits (Bagdad and San Manuel, AZ, and Bingham, UT) (*57*, p. 2245). The Bureau work has centered on the technology to recover these very large resources of rutile (*58*). Although the tests proved that the rutile could be partially recovered from these tailings, additional research will be needed before these could be considered a commercial source.

Clay deposits near Spokane, WA (400,000 mt contained TiO_2) (*2*), and bauxite deposits near Salem, OR (1.8 million mt contained TiO_2) (*2*), both contain presently unrecoverable ilmenite.

An ilmenite deposit in the San Gabriel Mountains of California contains possibly as much as 4.8 million mt of TiO_2 (*2*). The ilmenite, found in an anorthosite, may contain 45 pct TiO_2 (*28*), which could be upgraded by smelting.

Recent studies by the Geological Survey have outlined areas along the U.S. Atlantic Continental Shelf where heavy minerals may be present (*59*). Although very little work has been done on these offshore deposits, the potential appears to be significant. Large tonnages of ilmenite have been estimated to be present offshore south of New York City, in the inner New York Bight. This, too, is from recent work and remains under investigation (*60*).

Canada

The Allard Lake deposit in Canada is one of the most important titanium deposits in the world (fig. A-1). It occurs as massive dykes, sills, lenses, or irregular bodies associated with a local anorthositic intrusion within this Precambrian shield area. Ilmenite and hematite are the primary economic minerals. The deposit consists of three primary ore bodies: the Min ore body (the most important), the Northwest ore body, and the Cliff ore body. In total, the deposit is approximately 1 km long by 1 km wide. The open pit mine currently exploits approximately one-half of that area. Demonstrated resources for the three ore bodies at Allard Lake plus the Grader, Springer, and Mills ore bodies have been estimated, as of 1980, at 218 million mt at 31 pct TiO_2 (68 million mt contained TiO_2) and 36 pct Fe (*61*).

Although the Allard Lake deposits were explored throughout the 1940s, production did not begin until 1950. The mine was originally owned by Quebec Iron and Titanium Corp. (a company formed by Kennecott Copper Corp. and the New Jersey Zinc Co.). It is now owned by QIT-Fer et Titane Inc. (which is owned by Standard Oil Co. of Ohio).

The Puyjalon Lake and Magpie Mountain deposits, located near the Allard Lake deposits, were not included in this evaluation primarily because of the lack of information and the low grade of the ore. These two deposits are also asociated with the local anorthosites and, as with Allard Lake, are iron-titanium deposits. The Puyjalon Lake deposit has been reported to contain almost 210 million mt of ore with 11 pct TiO_2 and 18 pct Fe, while the Magpie Mountain deposit was estimated to contain 1 billion mt of ore with 11 pct TiO_2 and 43 pct Fe, both at the indicated level (*62*, p. 57).

The Pin-Rouge Lake deposit in Quebec was included in the evaluation (fig. A-1). As with the Allard Lake deposits, the deposit at Pin-Rouge Lake is also associated with an anorthositic core. The titanium mineralization is primarily ilmenite and is associated predominantly with the gabbros that rim the anorthosites. Hematite is also widespread and is associated with the ilmenite as well as some magnetite. The evaluation treated this deposit like the Allard Lake deposit in that a titanium slag and a pig iron byproduct would be produced.

The ore body at Pin-Rouge Lake was thoroughly explored in the 1950's by Laurentian Mines Ltd. and later, in the 1970's, by the Canadian Nickel Co. Ltd. (CANICO). Presently, Laurentian Mines Ltd. controls the 34 unpatended claims.

Pin-Rouge Lake is located approximately 50 km northwest of Montreal. The ore body, consisting of a main zone and its northern extension, contains numerous massive steep dipping lenses of ilmenite-hematite. Both zones are approximately 1.5 km in length, with widths ranging from 20 to 50 m. Published demonstrated resources for the Pin-Rouge Lake ore body are approximately 15 million mt averaging 20 pct TiO_2 and 27.6 pct Fe to a depth of 69 m (*63*). This is the equivalent of approximately 3.0 million mt contained TiO_2. Values used in this evaluation were somewhat higher based on unpublished sources.

The Athabasca Tar Sands of Canada were not included in this evaluation. This deposit, located in Alberta, is an oil sand, often termed a "tar sand," deposit that contains approximately 1 pct heavy minerals, of which titanium and zirconium minerals are the most notable (*64*). Various

Canadian companies such as Syncrude Canada, Great Canadian Oil Sands, and Canadian Titanium Pigments are investigating the feasibility of recovering these minerals from the tar sands (*65*). Total resources for this deposit have not been quantified.

Mexico

A titaniferous deposit, located at Pluma Hidalgo, Oaxaca, Mexico, was not included in this study. The titanium minerals present in this deposit are rutile and ilmenite. The deposit is similar in nature to those Virginia deposits included in the study and discussed earlier.

SOUTH AMERICA

Titanium resources in Brazil (fig. A-2) are found primarily in five mines and deposits, all of which were included in this analysis. Three of the deposits (Catalao, Bananeira, and Tapira) are proposed anatase operations, while the other two (Camaratuba and Campo Alegre de Lourdes) are ilmenite deposits.

Of the five mines and deposits, Camaratuba is the only one producing as of January 1984. Owned by Titanio do Brasil (TIBRAS) and operated by Rutilo e Ilmenite do Brasil S.A. (RIB), this operation began production sometime in late 1982 or early 1983 (*66*) producing an ilmenite concentrate and rutile and zircon byproduct concentrates. Camaratuba is located along the Grajua beach in the municipality of Mataraca between the States of Paraiba and Rio Grande do Norte. It is about 80 km south of the city of Natal. Exploration of the beach sand deposits in this region was undertaken by RIB in the late 1970's, with leases approved by the state in 1978. Construction of facilities preceeded until 1982 when startup was scheduled.

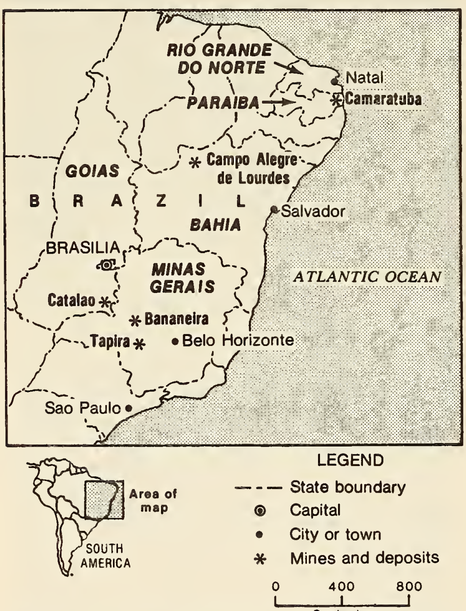

Figure A-2.—Location of titanium mines and titanium-bearing deposits of Brazil.

Camaratuba, a conventional secondary beach sand deposit of Recent age is a series of elevated sand dunes that lie between the ocean and an ancient sea cliff. The dunes stretch in a continuous line parallel to the shoreline, extending in a north-northwest by south-southeast direction for approximately 20 km. The dunes average 25 m high, and those that have been explored cover an area of approximately 10 ha. The total heavy mineral content of the sand is 5 to 6 pct, containing ilmenite, zircon, rutile, along with other, less important heavy minerals such as monazite, xenotime, garnet, and tourmaline.

The Campo Alegre de Lourdes deposit, located in the north-central part of the State of Bahia, 100 km northwest of Salvador, is the only other Brazilian ilmenite deposit included in this study. There are actually 10 individual deposits in that area grouped together for the purpose of this analysis. These deposits are associated with a regional intrusive gabbro within the Precambrian Brazilian shield, found in a small mountain range called Serra Dois Irmaos. The 10 deposits are Anfilofio, Branco, Carlata, Chico Velho, Lazan I, Lazan II, Redondo, Siyio, Testa Branca, and Tuicuiu (*66-67*).

These deposits are owned by Cia. Bahiana de Pesquisa Metais (CBPM), a state-owned company (70 pct), and Caraiba Metais S. A. (30 pct). The deposits were explored in the mid- to late 1970's, but no development ever occurred or was planned. It was assumed, based on the type of ore and the investigations made by CBPM, that the product from these deposits would be a titanium slag.

The deposits at Campo Alegre de Lourdes occur in a series of 10 north-south-oriented hills covering a length of 11 km, averaging 2.5 km wide. The resources are composed of a gabbro intrusive in the schist country rock. Two distinct zones are found at these deposits: the nonoxidized and the oxidized. Even though the nonoxidized rocks contain mineralization such as titaniferous magnetite, ilmenite, and other accessory minerals (rutile and various sulfides), the oxidized rocks contain the exploitable resources. In the oxidized rocks, ilmenite and leucoxene are the most prominent titanium minerals, averaging 20 pct TiO_2 in the ore (*67*). The ore zone averages 100 m wide and 1,000 m long (*67*). Measured and indicated resources at Campo Alegre de Lourdes have been reported to be 100 million mt of ore; the inferred resource could be as much as 500 million mt of ore (*68*).

The three anatase deposits included in the study are located in south-central Brazil. These deposits are unique in that the major titanium mineral is anatase, rather than rutile or ilmenite. Anatase has never been produced on a commercial scale, although significant testing has occurred at the pilot plant stage. There still remains some uncertainty in producing an untested product such as anatase.

The largest of the three anatase deposits is the Tapira mine in the State of Minas Gerais. It is approximately 400 km west of Belo Horizonte in a region already being mined for phosphate. The mine, which is in the development stages preparing for production, is owned by Cia. Vale do Rio Doce (CVRD). Most recent accounts show that the pilot plant work at this deposit is now completed and CVRD is constructing a plant that will produce a 90-pct-TiO_2 concentrate (*69*), which is anticipated to feed a chloride plant to be built in the city of Uberaba (State of Minas Gerais).

The Tapira deposit occurs in a large alkaline pipe (6.4 km in diam). Titanium ore is found in residual deposits overlying phosphate ore already being mined by Fertilizantes Fosfatados S.A. (FOSFERTIL). The alkaline pipe, or diatreme, is of late Cretaceous age, having intruded into Precambrian metasediments of the Canastra Group. The ore contains as much as 22.4 pct TiO_2 (at a 15-pct-TiO_2 cutoff), with resources reported to be approximately 190 million mt (*70*, p. 46). Resources used for this study were larger, using a lower cutoff grade. Demonstrated resources have been reported to be as large as 1.6 billion mt with more than 10 pct TiO_2 (*71*).

The Bananeira deposit, also in the State of Minas Gerais (Municipality of Patrocinio), is an anatase deposit with characteristics very similar to those of Tapira. The Bananeira deposit is actually composed of three deposits: Bananeira, Salitre II, and Sierra Negra. These deposits are located approximately 400 km west of Belo Horizonte, just north of the Tapira Mine. Bananeira is owned by Mineracao Itaqui, Ltd., which is owned by Cia. Brasileira de Mineracao e Metalurgia (CBMM). Ore from this deposit is being tested in a pilot plant.

The resources at Bananeira are in rock almost identical in age and characteristics to rock at Tapira. Resources have been reported to be 150 million mt averaging 22.4 pct TiO_2, using a 15-pct-TiO_2 cutoff (*70*).

The third anatase deposit evaluated is the Catalao deposit (also called Catalao-Ouvidor), located in the southern part of the State of Goias, approximately 350 km south of Brasilia. The owners of this deposit, Metais de Goias S. A. (METAGO) and Goias Fertilizantes S. A. (GOIASFERTIL) (a phosphate producer) have plans to do pilot plant studies on the ore at Catalao, although, as of this writing, no progress has been made.

The Catalao deposit is located just to the northwest of the Tapira and Bananeira deposits, and its geological characteristics are nearly the same. Resource data for this deposit are not available, although it is fair to assume that TiO_2 grades are very similar to those at Tapira and Bananeira.

Demonstrated resources used in this study for the three anatase deposits in Brazil total nearly 300 million mt of ore (over 75 million mt contained TiO_2). Inferred resources are an additional 145 million mt of ore (containing approximately 37 million mt TiO_2).

EUROPE

Finland and Norway have the two most important producing titanium mines in Europe at Otanmaki and Tellnes, respectively. Italy's Piampaludo deposit, in the feasibility planning stage, has a large potential. Titanium resources are found in Portugal and Spain, although they are small and rather insignificant. Romania and the U.S.S.R. also produce titanium products.

Finland and Norway

The Precambrian areas of the Baltic Shield characterize the titanium deposits of Finland and Norway. Deposits appear to belong to one main genetic type, being generally considered as differentiates from the crystallization of basic magmas. These deposits almost invariably show an association with provinces, complexes, or single bodies of mafic, less often ultramafic, igneous rocks in which anorthosites, gabbros, norites, and/or their metamorphic derivatives predominate. The two most important deposits are Otanmaki in Finland and Tellnes in Norway (*72*, p. 22; *73*). Figures A-3 and A-4 show the locations of these deposits.

The Otanmaki operation is Finland's only titanium producer. It is located 500 km north of Helsinki. The vanadium-bearing magnetite-ilmenite ore deposit is located on the northern flank of a large layered Precambrian hornblende gabbro-anorthosite intrusive. Amphibolite is the predominant rock type. The ore itself is the contact zone between the gabbros and anorthosites, and is made up of heterogenous anorthosites, gabbros, metagabbros, and orthoamphibolite. This zone is about 2.5 km long and 500 m wide and can be traced to a depth of 800 m. Several types of

Figure A-3.—Location of Finland's Otanmaki Mine.

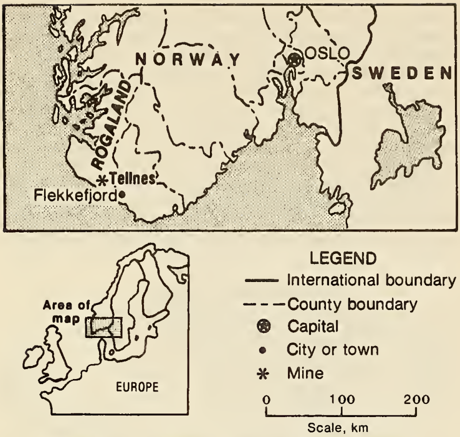

Figure A-4.—Location of Norway's Tellnes Mine.

ore are present: impregnation ores (low grade, less than 20 pct Fe) to massive ores (high grade, greater than 40 pct Fe). Individual ore bodies are lens shaped and range in size from 2 to 20 m long and 5 to 30 m wide. Their long axis is oriented east to west; dips are near vertical to vertical, and they plunge from 45° to 60° to the west. Average grades are 39 pct megnetite, 29 pct ilmenite (13.5 pct TiO_2), and 1.5 pct pyrite. Vanadium does not occur as distinct vanadium minerals but is contained in the magnetite at 0.9 pct (0.275 pct in the deposit). The deposit was discovered in 1938, by tracing titaniferous float material and by subsequent magnetic surveys. Exploratory drilling in 1939 delineated two ore bodies, Otanmaki and Vuorokas, approximately 3 km to the east. Construction and development of the mine, mill, and support facilities begun in 1951; a small amount of ore was hoisted in 1953. Over the years, production has increased to over 1.0 million mt/yr. Between 1953 and 1955, only concentrates of iron, ilmenite and pyrite were produced. In 1956, the vanadium pentoxide concentrate was added. This is now the most valuable product of the operation (*74-78*).

The Tellnes mine is located in southwestern Norway in the State of Rogaland, northwest of Flekkefjord. In the early 1950's, NL Industries' subsidiary Kronos Titan A/S realized that the accessible resources at its Storgangen Mine would soon be depleted. Exploration for other resources was initiated in 1954 using aeromagnetic surveying techniques, resulting in the discovery of the Tellnes ore body. Half of the ore body is under the waters of Tellnesvann (Tellnes Lake). The deposit is a large lens- or boat-shaped homogeneous ilmenite-norite intrusive in the Ana-Sira Anorthosite Massif of the Egersund Anorthosite Complex. It is a large complex covering 1,000 km² of southwestern Norway. The deposit is 2.7 km long and up to 450 m wide, covering 57 ha; mineralization was proven to a depth of 330 m. Diamond drilling indicated substantial ore resources of 200 to 300 million mt at 18 pct TiO_2 (39 pct ilmenite) and 23 pct Fe (2 pct magnetite). Resources used for Tellnes in this study are substantially larger. Production at Tellnes began in 1960 at 300,000 mt/yr and has increased to over 2.0 million mt. Three types of concentrates are produced: ilmenite concentrate at approximately 45 pct TiO_2, 35 pct FeO, and 12 pct Fe_2O_3; magnetite concentrate at 64.5 pct Fe, and 3.5 pct TiO_2; and a sulfide concentrate at 2.5 pct Cu, 4.5 pct Ni, and 0.7 pct Co (*79-83*). A potential slag operation in Norway was not included or discussed in this study because of a lack of information.

Italy

Italy's Piampaludo deposit could potentially be Europe's only natural rutile producer. The deposit is still undergoing feasibility studies. Piampaludo is located in northwest Italy (fig. A-5) in the province of Savona near the town of Piampaludo, about 13 km from the coast, 55 km (by road) from the nearest coastal cities of Genoa and Savona. The deposit consists of a low-grade eclogite. Eclogites are metamorphic rocks formed at extremely high temperatures and pressures during regional metamorphism. A massive and highly fractured ore body, the deposit is 1.8 km long by 500 m wide, covering 90 ha. Rutile, as an accessory mineral in eclogites, is disseminated throughout the entire ore body at approximately 3 to 5 pct. Industrial-grade garnet, at 25 to 30 pct of the deposit, is also recoverable. Diamond drilling has proven the existence of 150 million mt of ore at 6 pct

Figure A-5.—Location of Italy's Piampaludo rutile deposit.

TiO_2 (rutile plus ilmenite), with another possible 300 million mt at 5.8 pct TiO_2. Mineraria Italiana S.p.A. Milan, the owners, are looking for a joint venture in order to begin development and production (*84-86*).

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Although no deposits from Romania were evaluated in this study, there exist three deposits worthy of discussion. All heavy-mineral deposits in Romania are owned and operated by the Federal Government, Ministry of Mines-Geology.

The Chituc heavy-mineral deposit is located in the Dobrogea Province on the Black Sea coast. The mine was developed in the late 1970's and has been known to have produced at least at pilot plant scale. The plant produces an ilmenite concentrate along with some zircon and garnet. The ilmenite concentrate cannot be used for pigment production owing to its high nickel and chromite content. Resources at Chituc have been estimated to be approximately 200 million mt of ore grading 0.51 pct TiO_2 at the inferred resource level.

The Tigveni Mine is located on the River Topolog in Arges Province. It appears to have been in production since the late 1970's. The deposit consists of several heavy-mineral-bearing formations of late Pliocene to early Pleistocene age. The mine produces primarily an ilmenite concentrate although it is possible that zircon is also recovered as a byproduct. Identified resources at this deposit have been estimated at 50 million mt of sand grading approximately 1.0 pct TiO_2 from the ilmenite.

The Glogova-Sisesti deposit is located on the banks of the River Motru on the boundary between Mehedinti and Gorj Provinces in southwest Romania. Exploration at this deposit occurred in the late 1970's although further development is not thought to have taken place. The deposit consists of three heavy-mineral-bearing formations of late Pliocene to early Pleistocene age, similar to the Tigveni deposit. It appears that ilmenite, rutile, zircon, and monazite could all be recovered. Resources have been estimated at 340 million mt of sand grading 0.75 pct TiO_2 at the inferred resource level.

Union of Soviet Socialist Republics

Significant production of titanium in the U.S.S.R. began after World War II. The ilmenite-magnetite deposits of the Urals were the early sources. Since 1960, the fossil placer deposits in the Ukraine have assumed greater importance. Ilmenite is also obtained from titanomagnetite deposits in the Kola Peninsula. Other significant deposits of titanium in the U.S.S.R. are located in the Azov Coast, Kasakhstan, Siberia, Transbaikalia, and the far eastern provinces. Titaniferous magnetite deposits in the Caucasus Mountains of Armenia, discovered in the early 1970's, are also considered important, as well as titanomagnetite sands on the Kuril Island, Iturup.

By far the most important producing titanium deposits in the Soviet Union are the ancient heavy-mineral placers along the middle reaches of the River Dnieper in the Ukraine. Production is centered in two main areas near Kiev and Dnepropetrovsk, with the latter being more important. Heavy minerals at this deposit ocur in thin Cretaceous-Tertiary sediments overlying the northeast flank of the Ukrainian Massif. It appears that there are two types of commercial titanium placers in the Ukraine, ancient littoral marine placers and alluvial placers. Resources for these deposits are not known, although the ilmenite content of the sands averages 20 kg/m³, and some of the sands contain as much as 2,000 kg/m³.

Until the discovery and development of the Ukraine heavy-mineral placers, the titaniferous magnetite deposits of the Ural Mountains were the major source of ilmenite concentrates for the developing Soviet titanium industry. Iron ore mining is the main activity in the area, but a variety of other mineral concentrates are being produced including vanadium, titanium, and more recently, rare-earth minerals. Of the numerous mines in the Urals, it is believed that three of these at present are important titanium ore deposits, although it is known that other deposits do contain significant resources of titanium minerals. The three deposits are Gusevogorsk, Kachkanar, and Kopansk (Kusa), which occur in titaniferous magnetites related to basic, ultrabasic intrusive rocks, and amphibolites outcropping along the main range of the Ural Mountains. Total titanium resources in the Urals have been estimated as 132 million mt of ore at the inferred level averaging 10 pct TiO_2.

Important titanium deposits are found in the alkalic rocks of the northwest part of the Soviet Union, in the Kola Peninsula, and in the Karelia Autonomous S.S.R. Ores are primarily of the titanomagnetic associations and the main mining and processing acvitities in the area are centered in the iron ore formations. Five or six deposits are producing iron oxide and vanadium pentoxide concentrates, but it appears that only the Afrikanda Mine is actually producing a titanium dioxide concentrate, from perovskite and titanomagnetite. Resources for Afrikanda are not known, although they have been estimated as "large"; TiO_2 grades range from 8 to 18 pct. Other present and potential sources of titanium on the Kola Peninsula and in Karelia are the apatite-nepheline (aluminum) deposits at the Khibiny Massif and the titanomagnetites of the Pudozhgorsk, Tsaginsk, and Yelet Lake deposits.

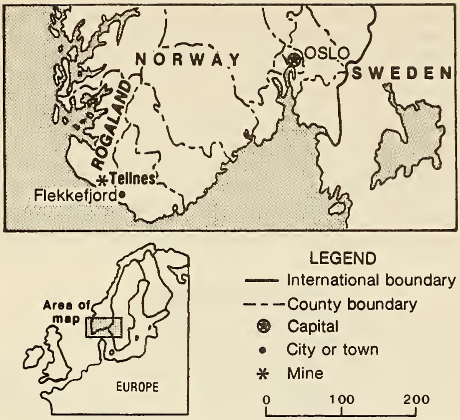
The most recent discovery of importance is the titaniferous magnetites of the Caucacuses, found in 1973. Deposits are referred to as Kamakorskoye and Svoranzkoye in the region of Armenia. The area is considered very promising for further exploration. These deposits may be suitable for iron ore exploitation with ilmenite as a byproduct. Resources, estimated based on dimensions, are in the order of 100 million mt of ore grading from 0.7 to 3.7 pct TiO_2, primarily from ilmenite.

ASIA

India-Sri Lanka

Beach sand deposits of India and Sri Lanka (fig. A-6) have been exploited for their monazite content since the early part of this century. Extraction of ilmenite and some rutile began in the 1920's in India and around 1961 in Sri Lanka.

India's heavy-mineral sand deposits are located on the west coast and peninsula tip in the States of Kerala (formerly Travancore and Cochin) and on the east coast in Orissa. Orissa Mineral Sands Complex, also known as the Chatrapur Sand Deposit, is India's largest and newest deposit, located 300 km southwest of Calcutta and 22 km northeast of Berhampur. It is planned to come onstream in 1985. The Chavara, or Quilon, sand deposit located on the west coast near the town of Quilon has produced ilmenite since 1932; monazite was probably recovered long before this. Peak production was reached in the 1940's as a result of



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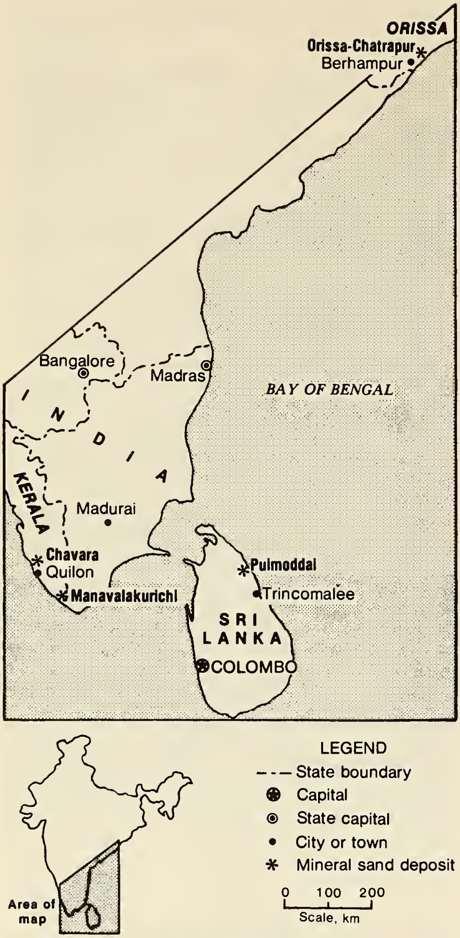

Figure A-6.—Location of India and Sri Lanka heavy-mineral sand deposits.

World War II. A third mineral sand deposit, located on the peninsula tip near the town of Triandrum, the M.K., or, more formally, the Manavalakurichi (also known as the Kayankomari deposit), has been in production since 1911 when monazite was recovered. By the mid-1920's ilmenite replaced monazite in importance. However, after Chavara was discovered, M.K.'s ilmenite was not as acceptable for market, at 54 pct TiO_2, as the ilmenite at Chavara, which is 60 pct TiO_2. Chavara's titanium is recovered as ilmenite and rutile concentrates, while M.K. produces ilmenite, synthetic rutile, and rutile. Orissa's sand deposit will produce only synthetic rutile (from ilmenite, 51 pct TiO_2) and rutile, as proposed in this study, although it may also produce monazite, zircon, and sillimanite.

Geologically and physiologically, many similarities exist between these deposits, including their coastal locations. Wave-action-formed sandbar deposits are the most commonly occurring deposits (*87*). With emergence, these beach deposits became buried by sand dunes. The Orissa-Chatrapur deposit is a system of transverse coastal and inland dunes separated by another system of lower dunes. Maximum elevation reached by these dunes is 17 m above sea level. This dune system is approximately Quaternary in age.

Sri Lanka has only one major heavy-mineral sand deposit, Pulmoddai, a beach deposit located about 58 km north of Trincomalee (China Bay) and 400 km northeast of Colombo. It is owned by the Ceylon Mineral Sands Corp. (CMSC). Pulmoddai began production in 1961, although heavy-mineral concentrations at Pulmoddai have been known since the 1920's. The deposit covers an area of 3.2 km^2 approximately 7.2 km long and 46 m wide. Ilmenite is the major economic mineral; however, rutile, zircon, and monazite are also present. Origin of these sands has not been firmly established, although the mountainous region at the center of Sri Lanka has been suggested. As an intermediate host of the heavy minerals, the younger Pleistocene and Recent rocks along the coast have been considered. Eroded material is transported by the Ma-Oya River to the Kokkilai lagoon north of Pulmoddai; from there it is carried southward by coastal drift and offshore currents to the Pulmoddai deposit area. A promontory at Arisi Malaa acts as a barrier to further southward development. Under appropriate conditions, monsoon storm waves attack the intermediary host rock and add additional material to the deposit. Drill-hole exploration of the deposit has yielded a consistant pattern of placer sands to a depth of 6 m, where Precambrian crystalline rocks are encountered (*88*).

Because of the confusing nature of published sources and confidentiality, Indian and Sri Lankan mineral sand resources are combined into a single number and not discussed on property-by-property basis. Demonstrated heavy-mineral sand tonnages are estimated at 552 million mt, with inferred resources of 455 million mt; total contained titanium is 40 and 44 million mt, respectively. Demonstrated resources contain ilmenite, 33.9 million mt, rutile, 5.1 million mt, and leucoxene, 0.6 million mt. Inferred tonnages are 41.6 million mt ilmenite and 2.1 million mt rutile.

Resources in Southeast Asia

Titanium resources in Southeast Asia were not included in this study because of the scarcity of data and the relatively minor impact of these resources on world titanium availability. The greatest potential for titanium resources in this region is from Malaysia where small-scale alluvial tin operations recover ilmenite and other heavy minerals; in aggregate they represent significant production. At these operations, ilmenite and many of the other heavy minerals are separated from the tin in the "amang" plants, using gravity and magnetic separation. Ilmenite concentrates range from 51 to 64.5 pct TiO_2 (*89*). Many of the ilmenite concentrates produced in Malaysia are sold to Japan. A synthetic rutile plant was built in 1976, but owing to market conditions, it has been inactive since 1980. Malaysia should continue to be a producer and net exporter of ilmenite concentrates so long as it is producing tin, although its exports of ilmenite will remain limited. The size of the resources of ilmenite in Malaysia is currently unknown and very difficult to quantify. Much of the ilmenite is stockpiled and never marketed.

A similar situation occurs in Thailand and Indonesia where ilmenite is also stockpiled as a byproduct from tin mining. These untreated resources of ilmenite, termed "amang" as in Malaysia, are currently unquantified. Ilmenite grades of treated amang have been reported to be over 53 pct TiO_2 (*90*).

Titanium resources also are found in Korea, Vietnam, Laos, Cambodia, the Philippines, New Guinea, and Japan. Most are small prospects of alluvial beach sands or are associated with tin mining as in Malaysia, Thailand, and Indonesia.

People's Republic of China

Resources in the People's Republic of China are not included in this study. The most significant deposits of titanium are at Sai-Lao, Wuzhuang (Hainan Dao), Xun Jiang, Beihai, Guangxi, Panzhihua (Sichuan), and other deposits in Guangdong Province. All titanium mines and deposits are Government owned and, in most cases, operated by farmer collectives.

Two producing titanium mines are located on Hainan Island off Guangdong Province (Sai-Lao and Wuzhuang). Mining has occurred on Hainan Island since the late 1950's The deposits are beach sands that have been concentrated along the coastline by wave action. The primary product produced at both these mines is ilmenite, although rutile, anatase, monazite, and zircon are also recovered. Resources for Sai-Lao have been estimated to be 203 million mt of sand (measured plus indicated) containing 1 pct TiO_2 (as ilmenite). Total heavy-mineral content at Sai-Lao is approximately 2.5 pct. Wuzhuang is a larger deposit totalling 508 million mt of sand (measured plus indicated) but averaging only 0.3 pct TiO_2 as ilmenite. The percent of heavy minerals at Wuzhaung is 1.5 pct.

The mines that are producing titanium products in the Guangdong Province (mainland) are feeding five heavy-mineral processing plants (Dianbai, Haikang, Xiton, Yangjiang, and Zhanjiang). The mines are producing from beach sands located along the coast that have been concentrated by wave action. These mines have been operating since at least the early 1960's. Ilmenite is the primary product from all of the mines, with monazite, rutile, and ziron also recovered. Demonstrated resources for the Guangdong Province operations are estimated to be 434 million mt with the TiO_2 ilmenite grades averaging 1.1 pct. The total heavy-mineral content averages 1.5 pct.

Ilmenite deposits of the Guangxi autonomous region are both river and beach sand deposits. Mines producing from these deposits feed a processing plant in the city of Beihai. Production of ilmenite began at Beihai in 1966, with small quantities of rutile, zircon, and monazite recovered in later years. In the late 1970's, a synthetic rutile plant was added to the operation for the purpose of producing welding rod coatings. Two-thirds of the heavy mineral concentrates feeding the Beihai plant originate in river sand rather than beach sand deposits. Indicated resources from the deposits feeding Beihai total 557 million mt of sand grading 0.7 pct TiO_2 from the ilmenite. Approximately 1.5 pct heavy minerals are contained in the sand.

A fairly high-grade explored ilmenite prospect in Guangxi is located along the Xun Jiang River. The deposit was discovered in the mid-1970's but has not yet been developed. Measured resources at this deposit have been estimated to be 66.7 million mt of sand containing 2.7 pct TiO_2 from the ilmenite. The heavy-mineral content of 6 pct is high compared with that of other deposits in Guangxi.

A large vanadium titaniferous magnetite deposit, called Panzhihua, is located between the cities of Dukou and Xichang in Sichuan Province. Various products are recovered from this operation including ilmenite, nickel, and cobalt (which is presently stockpiled), a titanium slag (which is discarded because of its vanadium), and steel ingots. The Panzhihua Iron and Steel Co. operates the processing plant, the blast furnace, and the steelmaking facilities. The operations at Panzhihua have been producing for many years, although the ilmenite concentrate has only been recovered since 1980. Proven (measured) resources at Panzhihua are just over 1 billion mt of ore, and as much as 5 billion mt of additional resources have been estimated at the indicated level. The ilmenite grade averages 9 pct. Some of the ilmenite resources are contained as tailings, which also average approximately 9 pct TiO_2.

AFRICA

Deposits containing titanium minerals in Africa are known to exist in Burkina Faso (formerly Upper Volta), Egypt, the Gambia, the Ivory Coast, Liberia, Madagascar, Malawi, Mozambique, Senegal, Sierra Leone, the Republic of South Africa, and Tanzania. Most of these deposits have not been extensively explored, have low tonnages and are too low grade to be of special interest. The two most important deposits, the only two African deposits evaluated in this study, are the Gbangbama area (also known as Mogbwemo) of Sierra Leone and the deposit at Richards Bay, Republic of South Africa.

Sierra Leone

Sierra Leone's heavy-mineral resources potential was established in 1954 with the discovery of rutile at Mogbwemo in the Sherbro River estuary of the Bonthe and Moyamba districts (fig. A-7), 100 km (400 km by road) from Freetown, Sierra Leone's capital city (*91-92*). Major production first occurred in 1967. Total area of the deposits is approximately 1,000 km^2. Mineral leases are held by Sierra Rutile Ltd., owned wholly by Nord Resources Corp. of Ohio. There are four separate deposits covering an area of 1,600 ha (called collectively in this report Mogbwemo), and the possibility exists that more deposits will be discovered. Principal deposits lie between the Gbangbama and Imperri Hills and in the coastal plain-tidal flats zone. Primary sources of the sediments containing the heavy minerals are the Precambrian garnetiferous gneisses and other metamorphic rocks and granite intrusions to the north and northeast. Deposits consist of layers of loosley consolidated interbedded sands and clays with occasional laterite cappings (*91*). Rutile is the only titanium mineral recovered, although ilmenite is present in recoverable amounts. Other heavy minerals are monazite, zircon, sillimanite, and staurolite. None of these are of sufficient quantities to be recoverable. Published resource tonnages of these deposits range from 110 to 187 million mt of sand averaging 1.5 pct to 2.0 pct rutile (*72, 93-95*).

Republic of South Africa

The Republic of South Africa has large resources of titaniferous ore in various types of deposits ranging from layered intrusions such as the Bushveld Igneous Complex, carbonatite deposits, and Kimberlite deposits to the numerous beach deposits, both fossil (located in the interior,

Figure A-7.—Location of Sierra Leone mineral sand deposit.

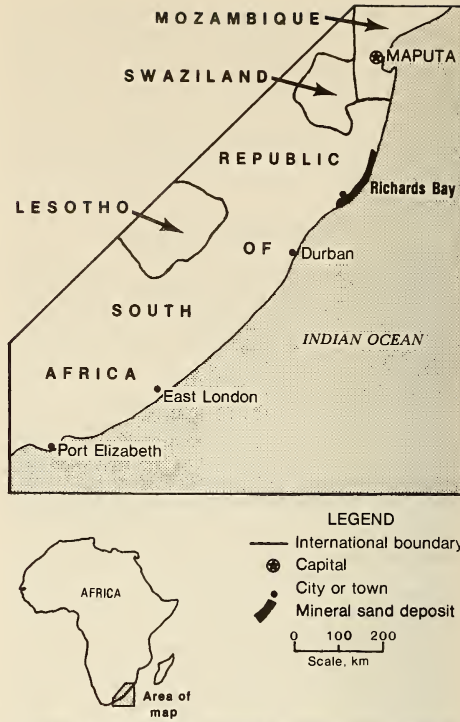

Figure A-8.—Location of Republic of South Africa's Richards Bay mineral sand deposit.

such as the Waterberg and Karroo systems) and the more recent deposits along the east coast, Richards Bay (*96*).

The most important heavy-mineral occurrences are located on the Republic of South Africa's east coast along a 965-km stretch between East London and the Mozambique border. Heavy-mineral concentrations, known to exist in this area since the 1920's, have an estimated total sand tonnage of about 2.3 billion mt, with heavy-mineral concentrations of 2 to 25 pct, averaging 9 pct. The east coast ilmenite deposits are of relatively low grade at 48 pct average TiO_2 content and 0.14 pct chromite. Rutile on the east coast runs about 91 pct TiO_2 (*96-97*), although as much as 93.5 pct at Richards Bay. Origin of the heavy minerals has not been established with any consistency. Suggested sources are the Karroo dolerite and stomberg basalt; however, the basalt contains more magnetite than ilmenite.

The Richards Bay Minerals operation (fig. A-8) is located along a stretch of eastern coastline, primarily north of the port-town of Richards Bay. Deposits of mineral sands occur as a Pleistocene coastal dune system about 2 km wide and aligned roughly parallel to the coast. Dunes attain elevations of 180 m and rest on the Port Durnford beds, a raised fossil beach formed by constructive wave action and representing an old high-water mark. Estimated sand tonnage is 750 million mt at 6 pct ilmenite, 0.25 pct rutile, and 0.4 pct zircon, with some garnet and a trace of monazite. Production began in 1977 with the output of rutile and zircon; in 1978, ilmenite and titanium slag were also produced.

South Africa's west coast dune deposits are unexploitable owing to the poor quality of the ilmenite, deposit size and configuration, and their remoteness.

OCEANIA

Australia

Australia's heavy-mineral beach sand deposits first attracted interest owing to their gold content. Between 1870 and 1895, small-scale operations continued intermittently to recover this gold. Possibilities of commercial exploitation of the heavy-mineral sand deposits were recognized by D. H. Newland, who was commissioned in 1928 by Titanium Alloy Manufacturing Co. of America (TAMCA), to report on the economic potential of these sands. Zircon-Rutile Ltd. began the first large-scale heavy-mineral sand mining operations in 1933-34, producing a mixed zircon-rutile-ilmenite concentrate for overseas shipment and sale to TAMCA (*98*, p. 8; *99*, p. 1; *100*, p. 51).

World War II, the Korean war, and interest in atomic energy increased demand for rutile, zircon, and monazite between 1939 and the early 1950's. Later work confirmed that the monazite content was insufficient for large-scale commercial exploitation. However, at the present time, some monazite is stockpiled for later processing to a 95-pct monazite concentrate for export markets. Establishment in 1954 of a commercial-scale metallic titanium industry in the

United States and Europe continued the increased rutile demand and helped the rutile market become independent of wartime activity (*98*, p. 8).

Much of Australia's heavy-mineral sand deposits are concentrated by wave action or by wind-sorting in both parallel and transgressive dunes. Wind-sorted heavy-mineral sand deposits generally do not compare in grade or size to wave concentrations. However, in some areas of extensive dune development, e.g., Fraser, Moreton, and North Stradbroke Islands, there are large quantities of low-grade heavy-mineral concentrations of economic importance. The interaction of tidal currents in protected waters is a third concentrating method. A large deposit of heavy-mineral sands exists on the southwest side of Moreton Island from the interaction of northern and southern tides. One dune deposit without any cover or interbedding of lower grade sand exists in a sheltered estuary area protected from waves and storm action. The concentration mechanism is not apparent but it does require a stable, long-continued concentrating condition. One mechanism is possibly the interaction of tidal currents and oblique waves resultant from east-southeast winds, which persist through most of the years, with constant accumulation over a lengthy period while the sea level gradually recedes (*99*, pp. 4-5).

The occurrence of zircon and rutile of similar type and grain size over about 1,700 km of coastline from just north of Curtis Island to just south of Sydney indicates derivation from more than one localized source. Accumulations of ilmenite are considered to be more from local sources such as the Mesozoic and Permian sediments of the Clarence, Moreton, and Sydney Basins. The origin of Western Australian heavy-mineral sand deposits is believed to be the Yilgarn Block, which supplied the sediments for the Pleistocene shorelines where these deposits occur. The source of Australia's coastal heavy-mineral sands is thought by many in Australia to be pegmatite and quartz veins of the Precambrian shield (*98*, pp. 27-31; *99*, p. 8; *100*, p. 73; *101*, pp. 21-23).

East Coast

Heavy mineral deposits on Australia's east coast occur along approximately 1,700 km of coastline, from the mouth of the Shoalhaven River, N.S.W., north to about Cape Clinton, Queensland. The 13 east coast deposits considered in this study are located between Sydney, N.S.W., and Curtis Island, Queensland, along nearly 1,400 km of coastline (fig. A-9).

Individual deposits range in size from 700 to 13,000 ha. Heavy-mineral concentrations commonly encountered are wave-concentrated deposits along present day beaches and/or in old strandlines. Wind-concentrated deposits are also present along the crests of beach and coastal dunes and the parallel and transgressive dune systems further inland from the shoreline. Estimated geologic age of these deposits has been placed at late Pliocene or early Pleistocene to Recent. Mineralogically, the four deposits of New South Wales (Evans Head, Munmorah, Tomago Sand Pits, and Yuraygir National Park) have a ratio of zircon-rutile to ilmenite of nearly 5.0 to 1.0, while the Queensland heavy-mineral deposits have a ratio of 0.54 to 1.0, a consequence of an increasing ilmenite content rather than a decreasing zircon-rutile content as the deposits go north. The ilmenite concentrate has a high chromite (Cr_2O_4) content, generally above 1.0 pct, and a low TiO_2 content, 56 pct or less, which makes it useless for the production of pigment unless upgraded to synthetic rutile first.

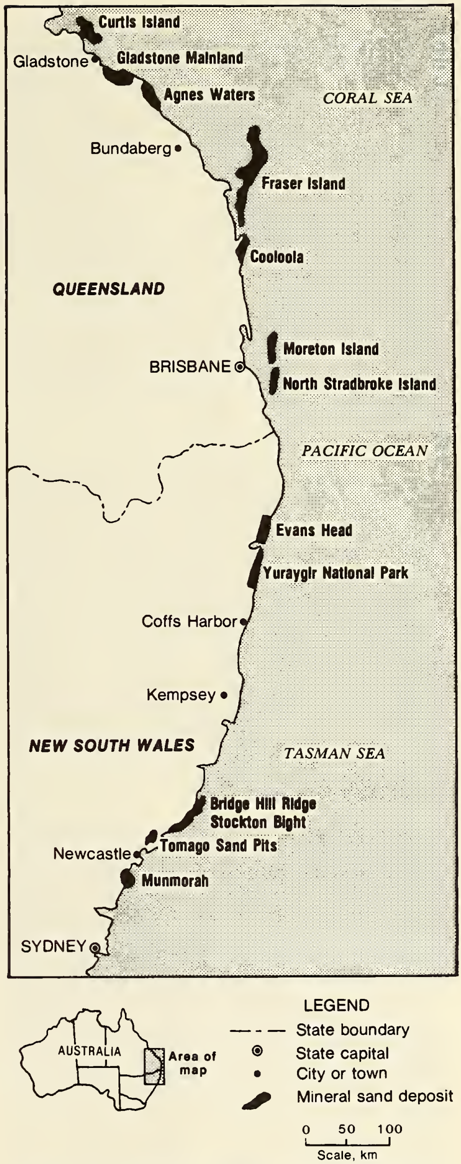

Figure A-9.—Location of Australia's east coast mineral sand deposits.

Munmorah-Tomago Sand Pits Area

Deposits in the Munmorah-Tomago Sand Pits area are located directly to the north and south of Newcastle, N.S.W. Rutile & Zircon Mines (Newcastle) Ltd. (RZ Mines) and Associated Minerals Consolidated Ltd. (AMC) own the Tomago Sand Pits Mine and the Munmorah deposit, respectively. Tomago Sand Pits was in production in 1982; Munmorah ceased operation owing to State mining bans enacted in 1977.

These deposits are concentrations of windblown sand, redeposited by aeolian erosion of older dunes. Heavy minerals average less than 2.0 pct of the total sand through the area. Rutile and zircon are the major ore minerals, and ilmenite and monazite are also available. These minerals represent over 90 pct of the total heavy minerals.

Published estimates of the Munmorah area are 578,000 mt of heavy minerals, averaging in terms of percent of the concentrate about 46.2 pct rutile, 22.7 pct zircon, 14.0 pct ilmenite, and 0.8 pct monazite (*102-103*). Mineral tonnages of the Tomago Sand Pits area were reported by RZ Mines in 1977 to be 640,000 mt of rutile and 670,000 mt of zircon (*104*).

Evans Head-Yuraygir National Park Area

The Evans Head-Yuraygir National Park area covers a coastline distance of about 100 km, approximately 40 km north of the Clarence River (Evans Head area) to 60 km south of the Clarence River (Yuraygir National Park area). Heavy-mineral deposits are mostly beach strandlines concentrated at the back beach line during storms. Age classification of deposits is Recent and currently forming.

This area was first mined for gold and plantinum between 1890 and 1900, with sporadic mining to the 1930's. Reported heavy-mineral content of this area is 130,000 mt with grades, in terms of percent of the concentrates, of 30.7 pct rutile, 21.6 pct ilmenite, 30.8 pct zircon, and 46.1 pct monazite. Current owners of this area are the McGerary brothers and both the Federal and State governments. Most of this area along the coastline is national park, and because of this, little production occurs (*101*, pp. 89-96).

North Stradbroke Island

North Stradbroke Island lies off the coast of Queensland, Australia, separated from the mainland by Moreton Bay. The island is approximately 35 km long and is 8 km at its widest point. Two companies own mining leases on the island: Associated Minerals Consolidated Ltd. (AMC) and Consolidated Rutile Ltd. (CRL). Heavy-mineral deposits on the island occur as beach strandlines, both present and buried, coastal and parallel dunes, and high and transgressive dune systems. The current island areas being mined are the old high-dune system of the eastern-central, central, and west coasts. These deposits are Pliocene to Pleistocene placer deposits formed by aeolian action. Large low grade heavy-mineral deposits are found to depths of over 30 m. In 1961, the average heavy-mineral grade was estimated to be 0.7 pct with a heavy-mineral composition, in terms of the percent of the concentrate, of ilmenite, 51 pct, rutile, 28 pct, zircon, 17 pct, and monazite, 0.12 pct (*99*, p. 16). More recent estimates of the heavy-mineral composition (*102*, p. 1062) are ilmenite, 50.1 pct, rutile, 15.8 pct, zircon, 12.5 pct, and monazite, 0.2 pct. AMC does not publish its heavy-mineral resources separately, only as part of the total of all its operations. Heavy-mineral tonnages reported in the CRL 1981 annual report are 1.5 million mt of rutile and 1.4 million mt of zircon. Both companies are currently mining their heavy-mineral leases on this island.

Moreton Island to Fraser Island

This area includes Moreton and Fraser Islands, plus the intervening part of mainland Queensland, covering about 215 km of coastline. The four deposits considered in this study are both the Mineral Deposits Ltd. (MDL) and Murphyores Holdings Ltd. leases on Moreton Island, the Cooloola deposit owned by the State of Queensland and the Federal Government, and the Fraser Island leases owned by Murphyores and Dillingham Minerals.

Moreton Island is situated about 60 km off the coast northeast of Brisbane, Queensland. It is approximately 40 km long and 9 km wide at its widest point. Four types of deposits exist on Moreton Island: (1) current beach deposits, (2) foredune and low-dune deposits near the beach, (3) high-dune areas, formed by the reworking of older dunes that existed at a higher sea level, and (4) some offshore and swamp areas. MDL lease holdings are mostly the high-dune areas of the island. Estimated heavy-mineral tonnage is about 3.6 million mt in 421.8 million mt of sand. Composition of the heavy mineral, in terms of the percent of the concentrate, is 42.8 pct ilmenite, 26.9 pct rutile, 16.6 pct zircon, and monazite (although no grade was reported) (*105*). Murphyores does not publish its lease holdings' sand and mineral tonnage. At the present time, neither owner is operating its leases.

The Cooloola deposit, located on the Queensland mainland in Cooloola National Park, stretches along 20 km of coastline. Deposits consist of beach concentrations, northwest-trending transgressive dunes, and frontal parallel dunes backing the beach areas. Windblown dune concentations occur on the crest of dunes to depths of 24 m. Here, as in other east coast deposits, rutile and zircon are the major economic minerals, about 18 pct to 20 pct, respectively, of the heavy-mineral fraction. However, ilmenite dominates the heavy-mineral fraction with a 59-pct average. Some monazite is also present at nearly 0.9 pct. No recent tonnage estimates have been published for this area. Since 1974, when the area was placed in the Australian national park system, all mining has been banned.

Fraser Island is located off the coastline of Queensland approximately 12 km east of Mary Borough. The island is about 122 km long and from 5 to 25 km wide. About 16,300 ha of land (10 pct of the total island area) was held as mineral leases in 1976 (*106*, p. 4). Deposits are largely high transgressive dunes and other areas similar to those at Cooloola. Murphyores and Dillingham Minerals jointly hold leases to the major mineralized areas, although mining is presently banned at Fraser Island because of environmental restriction by the Government. Most of the leases are located along the 123 km of eastern coastline, while some are on the south and west of the island. Estimated tonnages of these holding have not been published by the owners. Tonnage estimates in 1961 were about 1.0 million mt of heavy minerals along the east coast of the island. Composition of this estimate was 60 pct ilmenite and 16 pct each of rutile and zircon (*99*, p. 22-23).

Agnes Waters—Gladstone—Curtis Island

Three deposits, Agnes Waters, Gladstone, and Curtis Island are located along Queensland's central coastal section between Bundaberg to just north of Gladstone, about 150 km of coastline. The Agnes Waters deposit is located about

128 km north of Bundaberg near the small town of Agnes Waters. MDL holds the lease applications to 1,300 ha of land. This deposit comprises three generations of dune formation ranging from Pleistocene to Recent. Aeolian action and eustatic variations are the mechanisms of concentration. Rutile and zircon are the major ore minerals, with ilmenite and monazite as secondary minerals. A total of 2.7 million mt of heavy minerals with an estimated content, in terms of the percent in the concentrate, of 60 pct ilmenite, 10 pct rutile, and about 15 pct zircon, is present in 217.8 million mt of sand (*107*, p. 5). Extensive exploration and feasibility studies have been carried out; however, no development has taken place.

The Gladstone Mainland deposit is actually a number of deposits located from 15 to 60 km southeast of Gladstone. Mineral leases held by Murphyores total 3,331 ha (*108*). Both aeolian and wave action have formed the heavy-mineral concentrations of this deposit. These concentrations are found in low parallel dunes near the coast and on the beaches adjoining the low dunes. Values of the Gladstone area's heavy-mineral concentrations, in terms of the percent in the concentrate, are 65 pct ilmenite, 5 pct rutile (some places up to 10 pct), zircon averaging 16 pct, with monazite variable up to 0.2 pct. Total heavy-mineral tonnage is estimated at 2.6 million mt. Heavy-mineral content of the sand is 4.3 pct (*109*, pp. 17-18). Extensive reconnaissance drilling has been done throughout the area by Murphyores and other companies; however, no development has taken place.

The Curtis Island deposit is located near the Capricorn Peninsula on Curtis Island, approximately 40 km north of Gladstone. Approximately 300 km^2 of coastal dunes (2,726 ha) are covered by the deposit. Murphyores holds the mineral leases for the deposit. Concentrations of heavy minerals are found on the beaches and the northwest-trending parabolic dune system. The most recent heavy-mineral tonnage estimate (1968) is 705,000 mt containing concentrate with 78 pct ilmenite, 6 pct rutile, and 13 pct zircon. This represents only part of the Curtis Island tonnage (*109*, p. 18). Again, extensive reconnaissance drilling has been carried out although no development has taken place.

West Coast

Since 1956, the State of Western Australia has been a major ilmenite producer. Discovery and development of new deposits in the late 1960's to mid-1970's has continued this trend (*100*, pp. 61).

Titanium deposits of Western Australia (fig. A-10) are located on the Swan Coastal Plain from Busselton north to Eneabba (1,300 km) and on the Scott Coastal Plain, 160 km south of Busselton. The majority of these deposits are found within 400 km north and south of Perth, W.A., with the best ilmenite deposits occurring between Busselton and Bunbury. West coast heavy-mineral deposits were formed under conditions and mechanisms similar to those that formed the east coast deposits, and the west coast deposits occur within 2 or 3 km of the present coastline at or near sea level, or up to 70 km inland, as much as 130 m above sea level.

Concentrations of heavy minerals are found in "fossil" shorelines as buried strandlines and dune systems deposited in wave-cut platforms in the underlying Mesozoic basement rock, formed as a result of sea regression and coastline uplift during the Pleistocene epoch. A total of 850 million mt of sand at 9.6 pct heavy minerals has been estimated for this area. Ilmenite is the principal economic ore mineral estimated for the west coast. Two types of ilmenite are

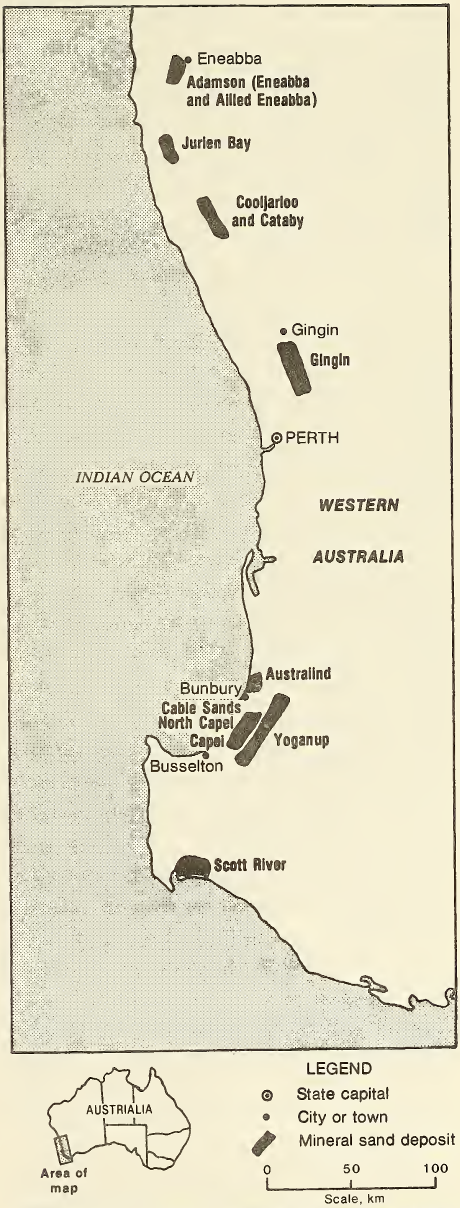

Figure A-10.—Location of Australia's west coast mineral sand deposits.

present, "altered ilmenite" at 65 to 85 pct TiO_2, which is suitable for pigment production via the chlorination process, and "pure ilmenite" at 52 to 54 pct TiO_2, which can be upgraded to synthetic rutile or can be used for pigment production via the sulfate process. Leucoxene, rutile, zircon, and monazite are of secondary importance (*100*, pp. 65-77; *110*, pp. 18-19; *111*, p. 419; *112*, p. 627).

An estimated total sand tonnage of 600 million mt averaging 10 pct heavy minerals from 14 deposits on the west coast was evaluated in this report. The heavy-mineral content, in terms of the percent of the concentrate, is 54 pct ilmenite, 14 pct zircon, 5.1 pct rutile, 4.4 pct leucoxene, and 0.4 pct monazite. The remainder includes other miscellaneous heavy minerals.

The most important ilmenite heavy-mineral area is located south of Perth (400 km), between Bunbury and Busselton. The deposits of Australind, Capel (north and south areas), and the Yoganup area (three deposits) are part of three "fossil" shorelines associated with the Whicher Escarpment. These deposits are lenticular in shape and occur in sequential units of conglomerate heavy-mineral sands and sandy silts and clays. They are found at the surface to a depth of 15 m, with an average ore zone thickness of 5 m. Total estimated sand tonnage is 162 million mt at 14.2 pct heavy minerals. The heavy-mineral fraction content, in terms of the percent of the concentrate, is ilmenite, 30 pct, zircon, 6.5 pct, leucoxene, 5.0 pct, rutile 0.5 pct, and monazite, 0.4 pct. Australind, owned by Associated Minerals Consolidated Ltd. (AMC), is undeveloped while the others are producing. Their owners are also AMC, as well as Westralian Sands Ltd.

Another major west coast heavy-mineral area, discovered in the late 1960's to mid-1970's, extends for 400 km north of Perth along the Gingin Scarp located approximately 70 km inland on the Swan Coastal Plain between the cities of Perth and Eneabba. These deposits are also associated with ancient shorelines 25 to 130 m above sea level and are a mixture of buried strandlines and dune systems formed during the Pleistocene epoch. Heavy-mineral concentrations occur within the same sequence of conglomerate and sandy silt and clay. Ilmenite is still the dominant titanium mineral at 50 pct of the heavy-mineral fraction. The remaining heavy-mineral fraction, in terms of the percent of the concentrate, is zircon, 20 pct, rutile, 8.5 pct, leucoxene, 4.2 pct, and monazite, 0.5 pct. Depth and thickness of these concentrations are similar to those in the Busselton-Bunbury area. Estimated total demonstrated sand at these six deposits [Cataby, Eneabba area two, Gingin, Jurien Bay and Cooljarloo] is 393 million mt containing 36 million mt of heavy minerals.

The Eneabba deposit is one of the most important rutile mines in the world. Production began there in 1974, and identified resources account for nearly 100 million mt of heavy minerals.

Deposit owners are Metals Exploration Ltd. and Alliance Minerals NL (Cataby), Associated Minerals Consolidated Ltd. (Eneabba), Allied Eneabba Pty. Ltd. (Allied Eneabba), Lennard Oil NL and Westralian Sands Ltd., (Gingin), Western Mining Corp. Holdings Ltd. (Jurien Bay area). Only the two Eneabba deposits are producing (*100*, pp. 72-73).

The Scott Coastal Plain, 160 km south of Busselton, is the newest area of heavy-mineral sand exploration and discovery in Western Australia. The Scott River deposit is located in the northwest corner of the coastal plain about 7 to 10 km inland. It was discovered in the mid-1970's. As in other west coast mineral sand areas, this deposit is also associated with former shorelines; however, the deposit suggests shore and backshore areas of former lake and river deposits rather than a coastal beach deposit. The ore zone is 9 m thick, with about 4 m of overburden. Leucoxene, rutile, and zircon together make up 20 pct of the heavy-mineral fraction, while ilmenite is 60 pct of the fraction. No reported tonnage was published for the deposit; however, a total tonnage of 10 million mt of heavy minerals at 10 pct for the total area is estimated to include the Scott Coastal Plain, Bremer Basin, and the Leeuwin Block. Ownership of the deposit area has probably reverted back to the State. A joint exploration project by Union Oil Co. and Samedan Australia Pty. Ltd. failed to find significant heavy-mineral content.

Barrambie (not shown on figure A-10), a hard-rock titanium, vanadium, and iron occurrence in Western Australia, was included in this study because of its potential as Australia's largest hard-rock titanium deposit even though no mine presently producing slag in the world has as low a grade of TiO_2. The deposit is owned by Ferrovanadium Corp. N.L. and is located approximately 420 km inland from Geraldton. Initial exploration began in 1968 with geological mapping, geophysical surveying, and percussion and diamond drilling detailing the mineralization. The vanadiferous titanomagnetite deposit occurs within an Archean anorthositic gabbro complex approximately 20 km long and 400 m wide. Drilling has indicated mineralization to a depth of 50 m. The deposit was first discovered in 1960 by H. J. Ward during aerial reconnaissance of the Murchison Goldfield. Gold has been produced from the deposit at various times. Total indicated tonnage of 27 million mt at 26 pct Fe, 15 pct TiO_2, 0.7 pct V_2O_5 was estimated based on the exploration. Another 415 million mt at the inferred resource level was also estimated, but no grades were established. Development plans call for open pit mining and production of titanium slag, low-manganese iron and flake vanadium pentoxide. The deposit is undeveloped and is undergoing feasibility and technical processing studies (*113*).

New Zealand

New Zealand's titanium-bearing sands occur on both the North and South Islands. Those on the North Island are associated with the Waikato River at Murina and Munukau Heads. South Island deposits are found on the west coast between Jackson Bay and Karamea; the most promising area lies between Barrytown and Westport. The South Island deposits contain the only significant ilmenite deposits in New Zealand. A churn drilling program begun in the late 1960's found sufficient quantities and grades of heavy minerals plus gold, scheelite, and cassiterite to indicate a viable deposit. The heavy-mineral concentrations are beach deposits formed by wave and wind action. Deposits occurring along the coastline from sea level to 20 m above sea level have overburden and deposit thickness averaging 1.4 and 5.2 m, respectively. Ilmenite is the titanium mineral of importance, at 4 pct of the total sand tonnage. Other minerals are rutile (0.1 pct), zircon (0.35 pct), monazite (0.001 pct), and gold (0.06 g/mt), along with scheelite and cassiterite. The ilmenite, however, is low in TiO_2 (47 pct) and must be upgraded to synthetic rutile or the sulfate process must be used for pigment production. Total sand tonnage of the area is estimated at 1.0 million mt (*114*, p. 16). Fletcher-Challenge Ltd. at one time had an interest in this property although no development was ever undertaken. If land for mining is ever developed, it would have to be bought or leased from various farmers, who use some of the area for grazing land.

APPENDIX B.—TITANIUM DIOXIDE PIGMENT

Under current technology, the two processes for producing TiO_2 pigment are the chloride process and the sulfate process. The two major factors that influence which process is selected are (1) the availability of the raw materials (ilmenite or titanium slag for the sulfate process; rutile, synthetic rutile, titanium slag, or leucoxene for the chloride process and (2) environmental concerns related to solid and liquid waste disposal (this problem is less severe for the chloride process than for the sulfate process). However, the diminishing supply of rutile resources is a concern to producers using the chloride process. A description of each process is given below.

CHLORIDE PROCESS

The chloride process was introduced commercially in 1956 by Du Pont. This process primarily utilizes as material feed stock, rutile, synthetic rutile, or other high-grade TiO_2 sources. The one exception is Du Pont's special patented process which uses a mixture of rutile, leucoxene, and ilmenite, ranging from 63 to 80 pct TiO_2.

For the chloride process, materials are chlorinated at 850° to 950° C in a fluid-bed reactor in the presence of oxygen and a carbon source. The products are titanium tetrachloride ($TiCl_4$) and other titanium and iron chlorides. The $TiCl_4$ is separated and purified by fractional distillation. The product is then oxidized with air or oxygen, yielding TiO_2. Typical recovery for the chloride process, depending on the TiO_2 content of the feed material, is 90 pct (*115*). This process is now able to produce both anatase-grade and rutile-grade TiO_2 pigments, although the anatase grade is usually a mixture of anatase and rutile (70/30).

SULFATE PROCESS

The majority of world TiO_2 pigment plants use the sulfate process. Their raw materials are ilmenite or titanium slag from ilmenite. In a typical sulfate process, feedstock is ground to minus 200 mesh, then leached with concentrated sulfuric acid, agitated with air, and heated to 110° C by steam in a batch reaction tank. The reaction requires an acid-to-ilmenite ratio of 1.3 to 0.8, with the ilmenite added over a period of from 15 to 30 min. A solid mass of soluble titanium and iron sulfate and insoluble compounds is produced. The soluble sulfates are dissolved by the addition of water or weak sulfuric acid. This solution is passed over scrap iron to convert all ferric sulfate [$Fe_3(SO_4)_2$] to ferrous sulfate ($FeSO_4$) if ilmenite was the feed material. The resultant solution is clarified by filtration. The clarified solution is then cooled to 10° C in vacuum crystalizers where about 50 pct of the ferrous sulfate precipitates out as copperas. After further concentration and filtration, the liquor containing soluble titanyl sulfate [$Ti(SO_4)_2$] is hydrolyzed by injection of steam. By careful seeding techniques, either an anatase-grade or rutile-grade titanium pigment may be produced. Typical titanium recoveries range from 80 pct to 85 pct TiO_2, depending on the TiO_2 content of the feed material (*115*).

TITANIUM PIGMENT PLANT COSTS

Table B-1 gives the capacity, capital, and operating cost of typical titanium pigment production for both the chloride and sulfate processes in various parts of the world (*116*). These costs include construction of all necessary facilities and infrastructure to initiate production and to produce a commercially marketable pigment product. Labor, energy, and material costs are also included. In some cases, as in Japan, the costs of pollution control equipment are included; these costs can add from $90/mt to $120/mt to the cost of titanium pigment production.

Table B-1.—Typical capital and operating costs of titanium dioxide pigment plants by region, January 1981 dollars (*116*)

Region and plant type	Capacity, 10^3 mt/yr TiO_2 pigment	Capital cost, 10^3 $	Operating cost, $/mt concentrate feed
Australia:			
Chloride	33,000	63,000	1,038.6
Sulfate	33,000	58,125	911.9
	50,000	74,600	710.7
Japan: Sulfate	33,000	88,300	[1]873.4
	50,000	120,000	[1]632.1
Spain: Sulfate	25,000	65,000	[1]509.2
	50,000	100,000	[1]487.9
United States:			
Chloride	[2]82,000	143,832	[2]821.7
Sulfate	[2]66,250	NA	[2]755.3

NA Not available.

[1]Costs do not include cost of feed material or depreciation or return on investment.

[2]Costs are averaged based on available data.

APPENDIX C.—TITANIUM SPONGE AND METAL PRODUCTION

There are two processes for the production of titanium sponge: the Kroll and Hunter processes. Both involve the use of magnesium or sodium to reduce $TiCl_4$.

The Kroll process, using magnesium, is the most widely used. The reaction takes place in a sealed, pressurized vessel, previously purged with argon or helium, from which a mass of titanium metal and soluble magnesium chloride ($MgCl_2$) are produced. This mass is removed from the reaction vessel by a special boring machine and washed to dissolve the $MgCl_2$. The $MgCl_2$ is sent to electrolytic cells that separate it into chlorine and magnesium metal, which are both recycled. The chlorine can be used in the chlorination of the titanium feed material, if necessary, and the magnesium metal is used in the reduction reaction.

The production of titanium sponge is only an intermediate process to the final production of the metal form. Special techniques such as double arc melting, electrolytics, or the iodide process are used to produce the metal. Estimated capital costs for titanium sponge plants range from $10,000 to $18,000 per annual ton of sponge produced. One total capital cost estimate is $138 million for a 7,000-mt/yr plant, with an operating cost of $5.49/lb of sponge (1982 U.S. dollars) (*117*).

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